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Coastal and Hydraulics Laboratory

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Compilation Report on the Effects of Distortion

From the Writings of John J. Franco and James E. Glover

Thomas J. Pokrefke, Jr.

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Final report

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ABSTRACT: In the 1930s, 1940s, and 1950s, the U.S. Army Engineer Waterways Experiment Station (WES) conducted several series of studies to investigate the effects of distortion, differing horizontal and vertical scales, on physical model results. This report presents the portion of those investigations conducted from 1954 to 1961. The results had not been previously published; however, the two WES researchers, the late Messrs. John J. Franco and the late James E. (Ed) Glover, had prepared various unpublished documents of these investigations. Therefore, this report is a compilation of those writings and supporting data, as well as this author's conclusions and applicability of the effects of distortion investigations to physical, movable-bed models using lightweight bed materials.

The investigations conducted by Franco and Glover involved two specific series of tests. Those series were:

a. Plan A, Series 1. These tests were conducted using distortions of 0, 2, 4, 6, 8, and 10. The horizontal scale used was 1:200 with subsequent vertical scales of 1:200, 1:100, 1:50, 1:33.33, 1:25, and 1:20, respectively. The tests were conducted following the Froude criteria to determine the appropriate velocity and discharge scales for these tests.

b. Plan A, Series 2. These tests were conducted using distortion ratios of 0, 2, 3, and 4. The horizontal scale used was 1:400. This series of tests was conducted somewhat different than Series 1, with the velocity held constant at the 0-distortion value and the depth varied from the 0-distortion to the 4-distortion value. The depth was then held at the 4-distortion value and the velocity varied from the 0-distortion to the 4-distortion value. Some of these tests were conducted with the Froudian scale relationships not followed to isolate either velocity or depth of flow impacts.

The results of the two series of tests conducted by Franco and Glover indicate that:

a. Based on the Series 1 tests, the effects of distortion on the results of models of a straight reach are negligible unless the flow is affected by a bend upstream.

b. Based on the Series 1 tests, flow around bends is affected by model distortion, and the effect extends for a considerable distance downstream depending upon the amount of distortion.

c. Based on the Series 1 tests, the current directions in models with distortions of 4 and higher and with curvilinear flow is affected to the degree that the influence extends to the downstream model limits.

d. Based on the Series 2 tests, the currents in a bend would be deflected toward the concave side of the channel as the linear-scale distortion is increased. The effect of distortion was generally progressive up to a point where the alignment of the currents was affected or controlled by the wall along the concave side of the bend. When this point was reached, increasing the distortion appeared to have little effect on the alignment of the currents.

e. Based on the Series 2 tests, with the same channel roughness, the factors varied as the model was distorted were velocity and depth. The test results with constant depth and with constant velocity indicated that changes in the width-depth ratio of the channel was the principal cause of the deviation in the alignment of currents in a bend.

f. Based on the Series 2 tests, increasing the roughness of the model channel as the distortion was increased would tend to reduce the effect of distortion. These results also tended to indicate that use of surface roughness sufficient to entirely overcome the effect of distortion would be impracticable.

Contents

Conversion Factors, Non-SI to SI Units of Measurements

Non-SI units of measurements used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters

Preface

Mr. Thomas J. Pokrefke, Jr. (retired), former Deputy Chief of Staff of the Coastal and Hydraulics Laboratory (CHL), prepared this report working in an emeritus position with the U.S. Engineer Research and Development Center (ERDC) at the Waterways Experiment Station (WES). Preparation of the report was accomplished under the direction of Mr. Thomas W. Richardson, Director, CHL, and the general supervision of Dr. William D. Martin, Deputy Director, CHL. The draft of this report was reviewed by Dr. Stephen Maynord, research hydraulic engineer, CHL, who provided helpful comments.

This report was actually a compilation of various writings of two former WES researchers, the late Messrs. John J. Franco and the late James E. (Ed) Glover, both retired Waterways Division chiefs. The study on the effects of model distortion were conducted over the period of study, 1954 to 1961, and this report is a compilation and organization of various unpublished reports, written status reports, notes, and internal reports of these investigations.

It was an honor for this author to compile the writings and data that Franco and Glover presented so many years ago. It is almost fitting that Mr. Franco, at the age of 95, passed away as this report was being completed. Perhaps it will be a legacy for Franco and Glover that their research lives on and has been brought to closure by this effort.

At the time of publication of this report, COL James R. Rowan, EN, was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

Background

First tests

In the 1930s, the U.S. Army Engineer Waterways Experiment Station (WES)[1] conducted a series of physical model tests to investigate the effect of model distortion on model results. Those tests included: (a) the effect of distortion on the content and distribution of kinetic energy in model streams, (b) the effect of distortion on the distribution of velocity in a model stream cross section, and (c) the effect of geometric and slope distortion on distribution of energy and tractive force in stream cross sections. The results of those studies were reported in three reports (USAEWES 1935a, 1935b, and 1936).

While these tests were truly state-of-the-art investigations concerning the effects of model distortion on the parameters addressed, the results lacked general application due to the fact that the researchers used site-specific models of particular river reaches. Therefore, there continued to be a need to conduct research on the effects of model distortion that would be generally applicable to physical modeling.

Second tests

In the late 1940s, WES initiated a study for the Office Chief of Engineers (OCE)[2] to investigate the effects of distortion on hydraulic elements in physical models. The first phase of these investigations involved experiments using a triangular-flume. Establishment of the testing methodology was initiated at the First Conference with Hydraulic Consultants on Effects of Model Distortion on Hydraulic Elements (USAEWES 1949). In that conference, Dr. Lorenz G. Straub, St. Anthony Falls Hydraulic Laboratory, suggested that these first tests be conducted using a triangular instead of a rectangular channel. The study progressed from that point, and the consultants, including Dr. Straub; Dr. Boris A. Bakhmeteff, Columbia University; Dr. Hunter Rouse, State University of Iowa; and Dr. Arthur T. Ippen, Massachusetts Institute of Technology, met two additional times in 1950 (USAEWES 1950a and USAEWES 1950b) to discuss this

[1] Later realigned to become part of the U.S. Army Engineer Research and Development Center (ERDC).
[2] Later referred to as Headquarters, U.S. Army Corps of Engineers (HQUSACE).

research with the WES staff in the Hydraulics Division (HD)[1]. The results of the triangular-flume tests were presented in a report WES published in 1957 (USAEWES 1957).

It should be noted that some preliminary exploratory tests were conducted for the triangular-flume study using a small rectangular flume 0.5 ft wide[2] and 8.0 ft long. Due to difficulties resulting from the short flume length and steep slope, another flume, 15 ft long, was constructed. As presented in USAEWES (1957), the results from these tests were not included in the report since small differences between model and prototype "…were completely obscured by discrepancies in the measured test data; the smallness of the test apparatus rendered fine measurements impractical, produced undue entrance and exit effects, and possibly introduced significant scale effects."

In the "Conclusions" section of USAEWES (1957), the following was presented:

> "Continuation of studies of this type should permit tabulation of certain parameters which would establish limits and effects of distortion for various types of models, but the field would have to be explored much more extensively before such parameters could be determined. A critical review of the benefits that might be derived from verses the costs and time involved in carrying the idealized studies of the first phase to completion indicates the desirability of discontinuing this phase, for the time being at least, in favor of a more direct and practical approach to the study effects of model distortion. Accordingly, future phases of this investigation will deal more directly with practical specific aspects of problems in this field."

Therefore, no additional tests were ever conducted using the triangular-flume to investigate the effects of model distortion. However, additional testing referred to herein as the Third Tests were initiated in 1954.

Third tests

In 1953, OCE authorized HD at WES to conduct a "Civil Works Investigation" addressing the effects of physical model distortion. The specific purpose of these investigations was to determine the effect of distortion on model results, the degree of distortion permissible in modeling streams of various characteristics for the study of various hydraulic problems, the best and most economical method of adjusting/calibrating distorted models having different hydraulic characteristics, and to obtain data which may be useful in the interpretation of model results. Two HD researchers, the late John J. Franco (retired Waterways Division chief) and the late James E. (Ed) Glover (retired Waterways Division chief), were the principal investigators on this study. Over the period of study, 1954 to 1961, Messrs. Franco and Glover prepared various unpublished, written

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[1] Later HD was established as the Hydraulics Laboratory, which was eventually combined with the Coastal Engineering Research Center (CERC) to become the Coastal and Hydraulics Laboratory (CHL).

[2] A table of factors for converting non-SI units of measurement to SI units is presented on page v.

status reports, notes, and internal reports of this series of investigations; however, to the best of this author's knowledge, none of the results were ever published as a WES or similar report. Therefore, it was this author's intention to compile the various writings from Franco and Glover as a report of their investigations of the Third Tests.

Throughout the report, and whenever possible, Franco or Glover will be given credit for specific points. It should be noted that this author has no input to the report until the final section of the report designated as "Epilog." It is this author's intention to present the data and results exactly as Franco and Glover did in the various documents reviewed and compiled for the report. Therefore, the thoughts, ideas, and conclusions are strictly from those two researchers. Also, all photographs and data plates included in this report are essentially as Franco and Glover had prepared them in the original documents. Most of the photographs and plates were simply scanned and reprinted; however, a few plates were only in draft form, so those plates were finalized trying to maintain consistency with the completed plates. It is this author's opinion that after almost 50 years of this data and study results going unpublished and unavailable for technical review and comment, the information included herein was worthy of the time and effort to compile and report these results on the effects of model distortion.

Until the "Epilog" section, the data, analysis, and results presented are those of Franco and Glover. Virtually all the words presented were written by one of those two; therefore, this author will not use quotation marks to indicate exact quotation, since in effect the entire report (up to the "Epilog" section) will be direct quotes from the various documents. However, where specific statements are made that are directly attributed to either Franco or Glover, they will be acknowledged as the originator.

One hydraulic parameter that was not addressed by Franco and Glover was Froude numbers for the various tests. Various tests were conducted with Froude number equal to the prototype, while others were conducted with Froude numbers greater or less than the prototype. Consideration of Froude number is presented in the "Epilog" section. If the reader is interested in the Froude number of the prototype or any specific test, see Table 6 in the "Epilog" section for those computed values. Also, when specific tests that Franco and Glover conducted are presented, the Froude number(s) for those tests will be stated in the title using parenthesis as being constant or varying as they relate to the prototype value.

Authorization and Funding

As general interest and an effort to have this report as complete of a compilation of these investigations on the effects of distortion as possible, this author was able to locate various funding and authorization documents. The information compiled from that effort is provided as follows:

a. Study was authorized by the Chief of Engineers in a letter dated 31 July 1953.

b. Project plan was submitted to the Chief of Engineers in a letter dated 11 January 1954, subject: "Civil Works Investigations – Transmittal of Project Plan for CW 809."

c. Study was approved in the first indorsement thereto dated 26 January 1954.

d. Funding: for FY55 - $20,000; FY56 - $49,000; FY58 - $13,008; FY59 - $10,000; and FY60 - $7,500. Total study funding covering 6 fiscal years of $98,508.

2 Testing Program for Effects of Distortion

Initial Testing Program

As originally conceived and proposed to OCE, the testing program to investigate the effects of distortion of physical models was divided into three phases.

a. Phase 1 was conceived to determine the effects of distortion on surface, middepth, and bottom currents. This phase was to study various plans with various controlled conditions.

(1) Plan A, Series 1 was to address distortions of 0, 2, 4, 6, 8, and 10 with varying water-surface slopes using Froudian discharge scales and a constant channel roughness.

(2) Plan A, Series 2 was conducted for distortions of 0, 2, 3, and 4. Tests with this plan and series included the following.

(a) Tests using Froudian velocity scales and constant roughness with a Manning’s n of 0.012.

(b) A test with the velocity scale and roughness constant.

(c) A test with the depth constant at the 4-distortion value, roughness constant at 0.012, and the velocity scale varied.

(d) A test with the depth and roughness constant and a varying velocity scale.

(e) Tests using the Froudian velocity and a roughness of 0.025.

(f) A test with the velocity scale constant at the 0-distortion value and roughness constant at 0.025.

(g) A test with the depth constant at the 4-distortion value, velocity scale varied, and a constant roughness of 0.025.

(3) Plan B was proposed to investigate varying channel bed slopes using the Froudian discharge scale and constant roughness. The tests for this plan were never conducted.

(4) Plan C was proposed to investigate varying the discharge scale to provide correct water-surface slope with a constant roughness. The

tests for this plan were never conducted.

(5) Plan D was proposed to be conducted using Froudian discharge scales and slope with different roughness. Tests for this plan were not conducted, although some of the tests conducted in Plan A, Series 2, may be similar to this plan.

(6) Plans E and F were to be conducted for different shaped channels, trapezoidal channel and navigation channel, but these plans were not tested.

b. Phase 2 was conceived to investigate the effect of various stream characteristics: different radii of curvature; different width-depth ratios; and other characteristics such as velocity, slope, and roughness. None of the tests proposed for Phase 2 were conducted.

c. Phase 3 was proposed to investigate the effects of distortion on movable-beds. These tests were to be conducted with a 5-ft-wide and 2.5-ft-wide flume with the possibility of adding additional tests in a wider facility (to be constructed) for testing greater width-depth ratios and bends with different radii of curvature. Based on information in various files, the 5-ft-wide tests were conducted, although the data from those tests could not be located, and the research was terminated before the flume could be modified and the 2.5-ft-wide tests conducted.

Modified Testing Program

Apparently, as flume design and construction and initial testing progressed, Franco and Glover modified the original testing program. After extensive research and efforts in locating study data and results, this author concluded that plans actually studied were very limited. However, the data and analysis for the tests that were completed are thorough and extensive. As already noted, the following tests were not conducted or were not completed:

a. Phase 1, Plan B.

b. Phase 1, Plan C.

c. Phase 1, Plan D.

d. Phase 1, Plans E and F.

e. Phase 2.

f. Phase 3 was initiated, but only half completed; therefore, no analysis can be made. Additionally, following an exhaustive search, the data for the completed tests could not be located.

Franco and Glover presented the results of the Plan A, Series 1 and 2 tests in the various documents; therefore, the modified testing program is composed strictly of those tests.

3 Study Scope, Purpose, and Test Facility

Study Scope

The study of the effects of distortion involved the investigation of the effects of model scale distortion upon discharge distribution, flow paths, velocity distribution, and other hydraulic characteristics by conducting tests in a model of a simple, hypothetical stream.

Study Purpose

The purpose of this investigation was to determine the effect of distortion on model results or similitude of models, the degree of distortion permissible in modeling streams of various characteristics for the study of various hydraulic problems, the best and most economical method of adjusting/calibrating distorted models having different hydraulic characteristics, and to obtain data which may be useful in the interpretation of model results. The purpose of conducting fixed-bed tests was to provide a basis for establishing definite trends by selecting a hypothetical prototype having characteristics which, when reduced to reasonable scale ratios, are measurable within the accuracy limitations of the available laboratory equipment.

Definition

Franco defined distortion in this way.

> Model distortion is defined as any variation in the physical geometric shape or slope of a model from the true geometry of its prototype. Several different types of distortion are employed in hydraulic models, depending in each case on the nature of the phenomena involved in the investigation and the kind, size, and purpose of the model. The most common type is the simple geometric distortion produced by constructing a model to two different linear scales, one for the horizontal dimensions (length and width) and one for the vertical dimensions (depth). Another distortion occasionally employed is produced by using three different linear scales for length, width, and depth. In other cases, models

constructed to only one scale for all linear dimensions are given a slope distortion to either increase or decrease the natural slope, depending on the particular need to be satisfied. It is also necessary in certain instances to apply to models already geometrically distorted additional distortion of the slope scale to achieve the desired purposes. In certain types of models, no distortion whatever is permissible.

Test Facility

The investigations of model distortion was conducted in a flume 95.7 ft long having a rectangular cross section 3 ft deep and 5 ft wide with a 90-deg bend having a radius of 10 ft (Plate 1). For all tests, the entire flume width was utilized and the depth was varied based on the specific degree of distortion being investigated for that test. The bend started about 23 percent and ended about 42 percent of the way down the flume. The invert slope of the flume was constructed with a slope of 0.000256. The flume was designed to permit the modeling of the selected hypothetical stream to a horizontal scale of 1 to 200, model-to-prototype, and variable vertical scale to produce distortions from 0 to 10. Distortion was accomplished in the flume by increasing the depth and velocity according to the Froudian relationships. It should be noted that the stations identified in Plate 1 and referenced in the study results are 100-ft stations along the center line and referred to the prototype, hypothetical stream.

Velocities were measured with a miniature cup-type velocity meter designed and constructed at WES for depths less than 0.5 ft, and a commercial type Gurley pigmey meter for depths greater than 0.5 ft. The range that model velocities could be measured in the flume was 0.1 to 7.0 fps. Surface currents were determined by tracing the path of a cylindrical float 0.05 ft in diameter with its length varied so as to always be submerged 6 ft (prototype) at the same proportion, depending on the degree of distortion under study, of the total water depth. A one-half ft (100-ft prototype) grid was used to track flow paths. Middepth current directions were obtained by tracing the paths of cross vanes suspended in the model. The vanes were 0.1-ft wide with their length varied with distortion equal to 20 percent of the water depth, which meant that a 10-ft (prototype) middepth segment of water was secured with each distortion. The vanes were suspended from a spherical float that was submerged to a depth that would provide a projected area normal to the direction of flow of 20 percent of the projected vane area. Bottom current directions were obtained by tracing the path of a small disk having a specific gravity slightly greater than water.

Franco and Glover found that the paths of successive current direction indicators crossed in many cases since currents were never steady but were continually switching back and forth. By taking the average of several indicators started at the same point and filling in gaps occurring between current direction lines with supplementary data, current trends became apparent even though current lines crossed in many cases.

Water was supplied to the flume from a comprehensive circulating system and was measured with venturi meters. Three venturi meters, including an 8” by 4”, 12” by 6”, and 20” by 10”, were used to obtain the wide range of discharges required for the testing. The total inflow capacity using these venturi meters was 30 cfs. Water was introduced into the headbay through a slotted pipe and discharged into the flume through a brick, baffle wall. Water-surface elevations were controlled by a slide-type tailgate, 5 ft wide at the downstream end of the flume. Water-surface elevations were measured by means of piezometers located along the center line and one-quarter and three-quarter points of the flume width. These piezometers were run to a central gage pit located in the facility. The flume was enclosed in a temporary shelter to eliminate the effects of weather conditions on the study results.

Hypothetical Prototype Stream

In order to have a basis for comparing the effects of the different degrees of distortion, physical characteristics of a hypothetical, prototype stream were chosen to use as a reference. Those characteristics were as follows:

a. Cross section: rectangular

b. Channel width: 1,000 ft

c. Channel depth: 50 ft

d. Average velocity: 10.0 ft/sec

e. Channel layout:

(1) 4,000 ft upstream of the bend

(2) 12,000 ft downstream of the bend

(3) 90-deg bend with a 2,000-ft radius

f. Roughness (Manning's n): 0.03

g. Slope of the water surface and channel bed: 0.000256

Scale Relationships

Franco and Glover used the accepted and standard Froudian scale relationships for physical modeling. The scale relationships used for this study are presented in Table 1.

Table 1
Froude-Number Scale Relationships

	Undistorted Model	Distorted Model
Length, horizontal	L_r	L_r
Length, vertical	L_r	Y_r
Area, horizontal	$(L_r)^2$	$(L_r)^2$
Area, vertical	$(L_r)^2$	L_rY_r
Time	$(L_r)^{1/2}$	$(L_r)/(Y_r)^{1/2}$
Velocity	$(L_r)^{1/2}$	$(Y_r)^{1/2}$
Discharge	$(L_r)^{5/2}$	$(L_r)(Y_r)^{3/2}$

Test Procedures

Test conditions were set up in the flume for each distortion in accordance with the Froudian scale relations presented in Table 2, and flow was permitted to stabilize before any data were taken. Data obtained during these tests consisted of the following:

a. Piezometer readings at the locations shown in Plate 1.

b. Photographs showing the paths of confetti upstream and downstream.

c. Surface, middepth, and bottom current directions.

d. Velocity cross sections at selected stations along the flume.

Table 2
Scale Relations for Plan A, Series 1 Tests

Distortion	Horizontal Scale	Vertical Scale	Velocity Scale	Discharge Scale
0	1:200	1:200	1:14.14	1:565,685
2	1:200	1:100	1:10.00	1:200,000
4	1:200	1:50	1:7.07	1:70,711
6	1:200	1:33.33	1:5.77	1:38,484
8	1:200	1:25	1:5.00	1:25,000
10	1:200	1:20	1:4.47	1:17,889

4 Test Results

Plan A, Series 1 (Constant Froude Number)

The first series of tests were conducted with models of various scale distortions (see Table 2) adjusted to conform to the Froudian relationship for discharge and velocity with the same channel roughness used for each model. The roughness selected for those tests was that required for similarity in the undistorted model, which corresponded to a Manning's n value of 0.012. Adjustments of the distorted models were accomplished by reducing the water-surface slope so as to provide for the correct depth within the model bend. This adjustment resulted in depths upstream of the bend slightly lower and depths downstream slightly higher than that required for strict conformity with the Froudian relationship. These tests were designed to determine the effects of distortion in models in which the addition of artificial roughness is impractical because of the nature of the problem being studied. A typical example of such a model would be a movable-bed model.

Glover conducted this series of tests under the general supervision of Franco, chief of the Waterways Branch, and Mr. E. P. Fortson, Jr., chief of the Hydraulics Division. Glover was the principal investigator and responsible for the study. Various technicians throughout the study assisted him; however, the exact identification of those individuals could not be gleaned from the documents available.

General

The results of the first series of Plan A tests are presented on Photos 1 to 8 and Plates 2 to 32 and are discussed in the following paragraphs.

Surface currents

Surface current directions are shown on Photos 1 to 8 and Plates 2 to 7. Although the photographs show the movement of confetti, while the plates show the path of a float submerged 6 ft, the general trends indicated by both were generally the same. Surface currents were not affected appreciably by distortion within the straight reach upstream of the bend. Within and downstream of the bend, surface currents tended to move towards the left flume wall (looking downstream) with this tendency increasing as the distortion increased. Photo 1 and Plate 2 indicate the surface currents in the undistorted model to be generally parallel to the sidewalls, except within the bend and a short distance downstream. The effect of the bend on surface current directions extended farther downstream as the distortion increased. This effect extended to about sta 92+00 for the undistorted model (see Plate 2) to about sta 122+00 with a distortion of 2 (Plate 3), and to the downstream end (and probably below the end of the flume) at sta 190+00 for distortions of 4 and higher (see Plates 4 to 7). Currents from the right wall moved toward the left wall (across the center line) as far downstream as sta 53+00, 84+00, 120+00, 150+00, 155+00, and 160+00 for distortions of 0, 2, 4, 6, 8, and 10, respectively. Therefore, as the distortion increased, the flow dynamics were such that the channel-crossing tendencies of the surface currents moved farther and farther downstream.

The greatest change in surface current direction occurred between the 0- and 2-distortions. While the left flume wall impacted all tests, the wall effects and limitation became evident with a distortion of 4, and became more pronounced with the higher distortions. These tendencies can be seen clearly on the upper half of Plate 8, which shows the comparative trends of the surface currents from sta 71+41.6 at the downstream end of the bend to sta 130+00.

Bottom currents

In the various documents, Franco and Glover always addressed the bottom currents immediately after the surface currents and then lastly, the middepth currents. This was due to the fact that the difference in middepth current directions was not as great for the different distortions as the differences observed between the surface and bottom currents.

Bottom current directions taken with the various distortions are shown in Plates 9 to 14. These data show trends that are similar but opposite to those indicated by the surface currents. Bottom currents in the straight reach upstream of the bend were generally parallel to the flume walls and were not affected appreciably by distortion. Bottom currents in the bend tended to move toward the right wall, with the tendency increasing with the increase in distortion. Currents from the left wall moved to the right wall only from as far downstream as sta 47+00 in the undistorted model, and as far downstream as sta 56+00, 64+00, 68+00, 70+00, and 84+00 for distortions of 2, 4, 6, 8, and 10, respectively. Therefore, as the distortion increased, the bottom currents crossed the channel from left to right farther downstream. It was noted during these tests that dye and plastic grains (specific gravity of 1.05) introduced along the left wall upstream of the bend would rise to the surface on the inside of the bend (near the right wall) with models having distortions of 6 or greater. Although the tendency for currents to move away from the left wall increased progressively with the distortion, the distance the currents moved toward the right wall increased very little with distortions above 2. This indicated that the flume wall began to affect bottom currents above the 2-distortion. While the right flume wall somewhat impacted all tests, the wall effects and limitation became evident with a distortion of 4, and became more pronounced with the higher distortions. The lower portion of Plate 8 shows this trend where the bottom current paths for distortions of 6 and greater are virtually identical starting at sta 110+00 and continuing downstream from that point.

Middepth currents

Middepth current directions taken with the various distortions are shown in Plates 15 to 20. These data show that there was some tendency for middepth currents to move toward the left wall in the undistorted model, with the tendency increasing as the distortion increased. Since surface currents were affected by distortion in a similar manner, Franco and Glover felt that it was probable that the floats that held the vanes used to measure middepth currents affected the movement of the vanes to some extent.

Comparative data analysis – surface and bottom currents

At this point in the documentation, Franco and Glover made some comparisons and analysis of the surface and bottom current data, presented in Plates 2 to 7 and 9 to 14, respectively. Since they felt that the surface float used in the data collection for those currents had influenced the middepth currents, the analysis did not include those data.

Comparative data on surface and bottom current directions taken from one point each at the downstream end of the bend (sta 71+41.6) are shown in Plate 8. These data indicate progressive variations in current directions with increasing distortion, with greater differences between models of the lower distortions than between those of the higher distortions. However, the effects of distortion extended progressively farther downstream from the bend as the distortion increased, and comparative plates similar to those shown in Plate 8 for points farther downstream would indicate lesser differences between models of the lower distortions and greater difference of the higher distortions. A comparison of the surface and bottom current directions for the same model, particularly those of the higher distortions, indicate the presence of helical flow within and downstream of the bend.

Velocity cross sections

Velocity cross sections obtained during this investigation are shown in Plates 21 to 32. It should be noted that the velocities presented are prototype velocities converted using measured values and the Froudian velocity relationship. These results indicated the velocity distribution to be fairly uniform in the straight reach upstream of the bend with the higher velocities moving toward the right wall when the bend was reached. Through the bend, the higher velocities were maintained along the right wall with no particularly prominent differences between the various distortions except that velocities along the right wall were increased slightly and those along the left wall decreased as the distortion increased. A comparison of the velocity distribution for the various models downstream of the bend indicated little significance in differences. At sta 76+00, velocities tended to increase along the bottom and decrease along the right wall as the distortion increased. This tendency continued to about sta 90+00, below which velocities tended to increase along the left wall and decrease along the bottom and surface with increase in distortion.

In another version of the study results, Franco or Glover (it was impossible to determine which) took the velocity cross-sectional data as presented in Plates 21 to 32 and rearranged that data by flume stations to get Plates 33 to 43 for sta 20+00, 40+00, 52+00, 56+00, 60+00, 64+00, 68+00, 71+41.6, 90+00, 130+00, and 190+00, respectively. In the writings of Franco and Glover, only sta 52+00, 56+00, 60+00, 64+00, 68+00, and 71+41.6 (Plates 35 to 40) were used in their analysis. The plates containing the other stations are provided here, but are used by this author in discussions in the "Epilog" section. Referring to Plate 1, it should be noted that the stations used by Franco and Glover are located in the bend with sta 71+41.6 being the station at the downstream limits of the bend. The analysis presented stated that no trends in velocity distribution could be established in the cross sections until about sta 56+00 where a slower velocity along the right wall developed as the distortion increased up to a distortion of 6 then velocities increased slightly with distortions of 8 and 10 (see Plates 36 to 38). This transition zone continued to sta 68+00 where the velocity along the right wall definitely decreased as distortion increased (see Plate 39). From about sta 52+00 to the end of the bend at sta 71+41.6 there was a marked difference in velocity distribution between distortions of 0, 2, and 4 and distortions of 6, 8, and 10 (see Plate 40). In the first three distortions, the velocity varied from approximately 10 fps at the right wall to 13 fps at about 150 ft from the wall. Velocities above 13 fps extended from a minimum of approximately 15 ft from the flume bottom to a maximum of 30 ft from the bottom. The second group of cross sections (distortions 6, 8, and 10) had velocities along the right wall of only 5 fps, which increased to 13 fps and 150 ft from the right wall. Velocities above 13 fps extended from the water surface to within 10 ft of the flume bottom.

Plan A, Series 2

General

The first series of these investigations of model distortion involved a general study to determine the effect of scale distortion on current alignment. Distortion for the first series was obtained by varying the vertical scale, which in turn affected depth (width-depth ratio) of the model channel and velocities. The second series of the investigation included tests designed to determine the relative effects of the two factors (depth and velocity) by varying each factor separately. Additionally, this series of the investigation also included tests of the effect of scale distortion with different channel roughness. The results of these Series 2 tests are presented in Plates 44 to 53.

Modifications from Plan A, Series 1 tests

As discussed by Franco and Glover, relative to the surface currents, the left flume wall affected the current patterns with a 4-distortion. Therefore, Glover modified some of the assumptions made at the beginning of the Plan A, Series 1 tests for the Series 2 tests. Glover thought that the flume sidewalls had an appreciable effect on current trends for distortions greater than 2; therefore, the assumed horizontal prototype dimensions were doubled for this test series making a 0-distortion vertical and horizontal scale ratio of 1:400. This resulted in a depth one-half as great as for the corresponding distortions in the first series of tests and made it possible to obtain a greater range of distortion before the side-walls of the flume had an appreciable effect. The increase in scale ratio and resulting small 0-distortion depth necessitated a change in the submergence of the water-surface current direction floats from 12 percent to 20 percent of the total water depth. No changes were made in the flume bottom slope or roughness for the initiation of the Series 2 tests.

It was also determined in the first series of tests that both surface and bottom current directions, although they were opposite in direction, indicated approximately the same progressive effort of distortion. Therefore, since surface current directions were the easiest to obtain, they were used exclusively to indicate the effects of distortion in the Series 2 tests. In order to facilitate the comparison of the effect of different degrees of distortion, as well as reduce the voluminous data required for complete surface current direction coverage, only the mean path of a minimum of six floats were obtained for several starting points and were used to indicate the effect of distortion.

Test conditions and procedures

In the first series of tests, the only variables involved to change distortion from one ratio to another were velocity and depth. In order to evaluate the effect of each of these variables, the second series of tests were conducted varying velocity and depth separately. While the first series of tests included distortion ratios from 0 to 10, the second series included distortion ratios 0 to 4. First the velocity was held constant at the 0-distortion value and the depth varied from the 0-distortion to the 4-distortion value. The depth was then held at the 4-distortion value and the velocity varied from the 0-distortion to the 4-distortion value. Scale ratios used in determining depths and velocities were based on a 1:400 linear ratio, undistorted model. The Series 2 tests with the specific test variables are listed in Table 3. It should be noted that for the Plan A, Series 2 Tests 7 through 10, the Froudian scale relationships were not followed to isolate either velocity or depth of flow impacts.

Table 3
Test Variables for Plan A, Series 2 Tests

Test Number	Velocity Based on Distortion Factor	Depth Based on Distortion Factor	Flume Roughness (Manning's n)
1-3	varying	varying	0.012
4-6	varying	varying	0.025
7	constant[1]	varying	0.012
8	varying	constant[2]	0.012
9	varying	constant[2]	0.025
10	constant[1]	varying	0.025

[1] Velocity held constant based on 0-distortion Froudian value.
[2] Depth held constant based on 4-distortion Froudian value.

Since the Series 2 tests involved different scales than the Series 1 tests, Table 4 presents the Froudian scale relationships for the various parameters used within this series.

Table 4
Scale Relations for Plan A, Series 2 Tests

Distortion	Horizontal Scale	Vertical Scale	Velocity Scale	Discharge Scale
0	1:400	1:400	1:20	1:3,200,000
2	1:400	1:200	1:14.14	1:1,131,371
3	1:400	1:133.3	1:11.54	1:615,609
4	1:400	1:100	1:10.0	1:400,000

Plan A, Series 2, Tests 1 to 3 (Constant Froude number)

These tests show resulting paths for different starting positions and were designed to provide basic data for use in comparing the effects of subsequent tests. The Manning's n roughness for these tests was 0.012. Results of these tests, shown in Plates 44 through 46, indicated that floats started at the downstream end of the bend (about sta 140+00 with the 1:400 horizontal scale) were deflected toward the left wall, but the differences in the deflection from one distortion to the next became progressively smaller as the distortion increased. These results, along with the results of the Series 1 tests, indicated that the currents in the bend would be deflected to the left (concave side of the channel) as the linear-scale distortion increased and that the distortion effect was progressive to a point where the alignment of the currents was affected or controlled by the wall on the left. When this point was reached, increasing the distortion appeared to have little effect on the alignment of the currents. Floats started in the middle of the bend (about sta 110+00) and 200 ft (Plate 44) from the right wall were deflected toward the left wall in much the same manner as those started at the downstream end of the bend; whereas, floats started 400 and 600 ft (see Plates 45 and 46) from the right wall behaved more like those started at the upstream end of the bend. With a wider channel of the same alignment, it is probable that the deflection of the currents would be somewhat greater, particularly with currents started near the upper end of the bend.

Plan A, Series 2, Test 7 – Effects of varying depth with constant velocity scale (Varying Froude number)

Results of varying the depth while maintaining the velocity at the 0-distortion value and a Manning's n of 0.012 are shown in Plate 47. Accordingly, the depth scale was changed to provide linear-scale distortions of 0 to 4 and width-depth ratios of 1:40 to 1:10. Flow current trends from sta 140+00 near the downstream end of the bend showed a progressive increase in deflection toward the left wall with increase in depth similar to that obtained when the velocity scale and depth were changed (compare Plate 47 with Plates 44 through 46). The difference in deflection toward the left wall between the 0- and 4-distortion depths at sta 280+00 were 1,200, 1,050, and 1,000 ft for floats started 200, 400, and

600 ft from the right bank, respectively. This compares with deflections of 1,400, 1,050, and 1,100 ft at the same location between the 0- and 4-distortions of velocity and depth. Therefore, changing the depth based on the distortion factor (width-depth ratio) without changing the velocity scale produced only slight differences when compared to distorting the velocity and the depth relative to the distortion ratio.

Plan A, Series 2, Test 8 – Effects of varying velocity with constant depth scale (Varying Froude number)

Results of varying the velocity while maintaining the 4-distortion depth in the channel having a Manning's n of 0,012 are shown in Plate 48. In this test, the velocity scale varied from that required for a 0-distortion to that required for a 16-distortion (based on the horizontal scale), which meant that the velocity scale ranged from 1:20 to 1:5.0. The results indicated that changing the velocity scale had little effect on the current alignment. Although the velocity was varied, only small differences, with no apparent progression in current trends for the different velocities, were obtained. The alignment of the currents for these tests was about the same as that obtained with the 3-distortion in Tests 1 through 3 (compare Plate 48 with the top sections of Plates 44 through 46 for the 4-distortion tests). Glover concluded from this test that varying the velocity scale, as is often required in movable-bed models to obtain bed movement, would have only a small effect on current directions and flow distribution.

Effects of roughness on distortion effects

Up to this point all tests conducted in the distortion effects flume used a Manning's roughness of 0.012. The final portion of the Series 2 tests were undertaken to determine the effect of roughness on the study results. According to Glover, this corresponds to some studies such as movable-bed model studies in which the bed material automatically determines the channel roughness. In order to evaluate the effect of roughness on distortion effects in those types of models in which control of the roughness is possible, the flume was lined with expanded-metal on both sides and the bottom. With the expanded-metal installed in the flume, the channel roughness essentially doubled to a Manning's n of 0.025. According to the Froudian relationship, if the roughness (as represented by Manning's n) of the flume is assumed correct for the 1:400 scale undistorted model tests, the roughness of the flume with the expanded-metal installed would be approximately correct for the 3-distortion. The flume slope was fixed (0.000256); therefore, when the model water surface was adjusted to give the proper depth in the bend, the error in the water depths were greater upstream and downstream of the bend than was the case with the lower roughness values. The reduced depth at the upstream and downstream ends of the model made it impossible to obtain data for the 0-distortion in this portion of the Plan A, Series 2 tests. Therefore, Tests 4 through 6, 9, and 10 were conducted the same as Tests 1 through 3, 8, and 7, respectively, except the roughness was increased to 0.025.

Plan A, Series 2, Tests 4 to 6 (Constant Froude number)

As a result of the increase in roughness and limited depth, it was impractical to conduct tests with the 0-distortion. However, the results of tests with distortions of 2, 3, and 4, shown in Plates 49 to 51, indicated that the deflection of surface currents to the left was about 300 to 400 ft (prototype) less than with the lower channel roughness (compare Plates 44 to 46 with Plates 49 to 51). According to Franco and Glover, these results tended to indicate that increasing the channel roughness could reduce the effects of distortion.

Plan A, Series 2, Test 10 – Effects of varying depth with constant velocity scale (Varying Froude number)

This test was conducted with a constant velocity scale, same as for the undistorted model, and the depth scale was changed to provide a distortion of the linear scales of 2, 3, and 4. This test was the same as Test 7 (Plate 47) except that the higher channel roughness was in place. The surface currents from this test, shown in Plate 52, indicated that the results were generally the same as with the lower channel roughness, except that the deviations in the currents between the 2- and 4-distortions were from 100 to 350 ft (prototype) less than with the lower roughness (compare Plates 47 and 52). This continued to support the conclusion that Glover determined from Plan A, Series 2, Tests 4 to 6 that increasing the channel roughness could reduce the effects of distortion.

Plan A, Series 2, Test 9 – Effects of varying velocity with constant depth scale (Varying Froude number)

This test was conducted with the depth scale maintained the same as with the 4-distortion and the velocity scale varied, based on the horizontal scale, from that required for a 0-distortion to that required for a distortion of 8. This test was identical to Test 8 (Plate 48) except the higher channel roughness of 0.025 (instead of 0.012) was in place in the flume. The results of Test 9, shown in Plate 53, indicated that with the depth constant the alignment of the currents was not affected appreciably by changes in the velocity scale from 1:20 to 1:7.07. These results were generally the same as with the lower roughness (Test 8 in Plate 48), except that the deflection of the currents to the left was about 500 ft (prototype) less with the higher roughness.

5 Analysis of Test Results

Discussion of Results

Franco noted that the investigation covered by this research was conducted with models of a hypothetical stream and that no prototype data were available for use in determining the accuracy of the model results. For the purpose of evaluating the effects of distortion, it should be assumed, therefore, that the results obtained from the undistorted model would be accurate reproductions of similar results that would be obtained from a prototype having the characteristics of the hypothetical stream. Franco considered this assumption to be reasonable since the undistorted model was operated in accordance with the accepted laws of similitude. However, because of the small vertical scale of the undistorted model and the accuracy limitations of available equipment, Franco stated that the effects of model distortion should be based upon general trends rather than upon small differences in local measurements.

The Plan A, Series 1 tests were designed to provide information on the effects of distortion in models in which roughness of the boundary cannot be adjusted because of the nature of the problems involved. Models of this type are movable-bed models in which the roughness is controlled to a large extent by the grain size of the bed material used, and fixed-bed models in which the measurement of bottom current directions and velocities are involved. For this series of tests, the bed slope for all models was that required for the undistorted model, which was the same as the hypothetical stream prototype slope. This resulted in a maximum error in depth and average velocities for all models of about 0.5 percent, which occurred at the downstream end of the test reach with the error decreasing to zero as the bend was approached. Using the theoretical slope of a distorted model adjusted in the same manner, the maximum error in depth and velocities would have been about 5 percent, since the slope of the bed would have been increased by an amount equal to the prototype slope times the amount of distortion.

Conclusions

In general, the results of the Plan A, Series 1 tests indicated that model distortion tends to affect the results of models of streams in which curvilinear flow is involved. The effect of distortion is particularly noticeable on current directions within and downstream of a bend. The following conclusions were reached for the tests conducted for the Plan A, Series 1 and 2 tests:

a. Based on the Series 1 tests, the effects of distortion on the results of models of a straight reach are negligible unless the flow is affected by a bend upstream.

b. Based on the Series 1 tests, flow around bends is affected by model distortion, and the effect extends for a considerable distance downstream depending upon the amount of distortion.

c. Based on the Series 1 tests, the current directions in models with distortions of 4 and higher and with curvilinear flow is affected to the degree that the influence extends to the downstream model limits.

d. Based on the Series 2 tests, the currents in a bend would be deflected toward the concave side of the channel as the linear-scale distortion is increased. The effect of distortion was generally progressive up to a point where the alignment of the currents was affected or controlled by the wall along the concave side of the bend. When this point was reached, increasing the distortion appeared to have little effect on the alignment of the currents.

e. Based on the Series 2 tests, with the same channel roughness, the factors varied as the model was distorted were velocity and depth. The test results with constant depth and with constant velocity indicated that changes in the width-depth ratio of the channel was the principal cause of the deviation in the alignment of currents in a bend.

f. Based on the Series 2 tests, increasing the roughness of the model channel as the distortion was increased would tend to reduce the effect of distortion. These results also tended to indicate that use of surface roughness sufficient to entirely overcome the effect of distortion would be impracticable.

It is worth noting at this point that one of the conclusions from the earlier triangular-flume study of distortion effects (USAEWES 1957) was:

> "Velocity profiles show that increasing the degree of distortion greatly magnifies the intensity of secondary or transverse currents, thereby affecting the similarity of velocity profiles. This may have an important significance, especially where lateral diffusion of material is an object of study with distorted channels."

This is identical to a portion of conclusion *d* as it related to deflection of the currents. The reader is reminded that the triangular-flume study was conducted in a straight flume, so the researchers there also saw the impacts of increased distortion on flow distribution and energy within the channel. As pointed out from the triangular-flume study and can be interpreted from conclusion *d*, this magnification of the secondary currents can influence the movement of bed material if a movable-bed model study is conducted.

Theoretical Considerations

Franco considered the results and limitations of the effect of distortion study and provided some theoretical considerations. Franco wrote in discussing the

Series 1 tests that the investigation had not proceeded sufficiently to permit the establishment of even general laws concerning the effects of distortion in models of various types of streams. In the Plan A, Series 1 tests, the shape and dimensions of the model stream in a horizontal plane, surface roughness (Manning's n), and bottom slope were the same for all models. Since the water-surface slope for each model was the same as the bottom slope for all practical purposes (within 0.5 percent), the only variables between the models were the depth and velocity. These tests, therefore, indicated that the effects of distortion is a function of one or both of these factors, since the difference in the model results and the value of these factors increased with the amount of distortion.

Research conducted by various experimenters (Franco did not specifically identify the experimenters) indicate that helical or spiral flow in a bend is generated by the superelevation of the water surface towards the outer wall in conjunction with friction which greatly decelerates water flowing near the bed. The fast moving surface flow forced against the outer wall by centrifugal force creates a head along the wall (superelevation) which tends to force the slower moving bottom currents toward the inner wall. Since superelevation is a function of centrifugal force, proportional to the square of velocity, it increases directly with distortion. In other words, the superelevation in a model having a distortion of 2 will be twice that in the undistorted model. Also, introducing distortion in a model changes the width-depth ratio of the model channel from that of the prototype or the undistorted model. This ratio is usually smaller since, for practical considerations, the horizontal scale in a distorted model is generally made smaller than the vertical scale. This change in width-depth ratio will tend to increase the difference between the fast surface currents and the slow bottom currents, making it easier for the latter currents to be moved toward the inner wall.

Franco continued the consideration of the effects on distortion as it relates to centrifugal force by addressing this issue directly. Since the differences in the results obtained with the distorted models from those with the undistorted model were noted only in the reach affected by curvilinear flow, it is believed that centrifugal force should be considered as a possible factor in the analysis of the effects of distortion on flow patterns. The basic formula for centrifugal force is:

$$F = \frac{WV^2}{gR} \qquad (1)$$

where

F = centrifugal force

W = weight

V = velocity

g = gravity constant

R = radius of curve

The centrifugal force ratio, model-to-prototype, using the same fluid and the same gravity constant becomes:

$$f = \frac{wv^2}{r} = \frac{l^2dv^2}{l} = ldv^2 \qquad (2)$$

where

l = horizontal scale

d = vertical scale

For models operated in accordance with the Froudian relationship for velocity, Equation 2 becomes:

$$f = ld^2 \quad \text{(distorted models)} \qquad (3)$$

and

$$f = d^3 \quad \text{(undistorted models)} \qquad (4)$$

since v equals $d^{1/2}$ in an undistorted and distorted model and l equals d in an undistorted model.

It can be seen from Equations 3 and 4 that centrifugal force was a variable in the investigation completed since d and v were variables. The relationship of the centrifugal forces for the various models used in the investigation for the Plan A, Series 1 tests are shown in Table 5. The various horizontal and vertical scales used on the Series 1 tests were presented in Table 3.

Table 5
Centrifugal Force Ratios

Distortion	Centrifugal Force Scale	Centrifugal Force Ratio
0	1/8,000,000	1
2	1/2,000,000	4
4	1/500,000	16
6	1/222,178	36
8	1/125,000	64
10	1/80,000	100

It can be seen from this table that centrifugal force increased with distortion and that the centrifugal force of the 2-distortion model was 4 times that of the undistorted model, while the centrifugal force in the 10-distortion model was only about 1.5 times the centrifugal force in the 8-distortion model. Therefore, if centrifugal force is the factor affecting the results of the various distorted model, the difference in the results should increase progressively from that of the undistorted model and the difference between the results obtained in the undistorted and the 2-distortion models should be much greater than the difference between those obtained in 8- and 10-distortion models. The study results presented previously indicated this very trend (see Plate 14) and were reinforced with the Plan A, Series 2 tests for distortions of 0 to 4 (see Plates 44 to 46).

Based on this analysis, Franco concluded that the probability that the centrifugal force for the models in Plan A, Series 1 should have been the same for similarity of flow pattern. If such was the case, it would mean that similarity of flow patterns between a distorted model and the prototype can be obtained by making the centrifugal force in the distorted model equal to that which would be obtained in an undistorted model having the same horizontal or linear scale

or $$ldv^2 = l^3 \tag{5}$$

This will usually require a reduction in the ldv^2 factor. Since the length and depth are fixed by other considerations, the ldv^2 factor can usually be reduced more readily by a reduction in the velocity scale. The velocity scale would then become

$$ldv^2 = l^3$$

or $$v^2 = \frac{l^3}{ld} = \frac{l^2}{d}$$

and $$v = \frac{l}{d^{1/2}} \tag{6}$$

Using the same Equation 6 for undistorted models, we have

$$v = \frac{l}{d^{1/2}} = \frac{d}{d^{1/2}} = d^{1/2} \tag{7}$$

which is the Froudian relationship.

It should be noted that the velocity scale obtained from Equation 6 is based upon the indicated requirement to obtain similarity in the flow patterns in a horizontal plane between model and prototype. This does not obviate the requirement that distorted models be operated in accordance with the Froudian relationship for velocity for the study of flow lines and the effects of changes on water-surface elevations. However, it may be advisable to conduct studies in certain distorted models based on two velocities scales, one for the study of flow lines and the effects of improvements on gage heights, etc., and the other for the study of current directions and velocity distribution.

6 Epilog

This author worked directly for Mr. Glover for almost 20 years and with Mr. Franco for 5 years, before he retired, and then another 15 years or so in his consultant position to the Hydraulics Laboratory. Although, to the best of my recollection, the effects of distortion tests were never specifically addressed in conversations relative to physical modeling, it is apparent now that the knowledge and results indicated from those tests were totally integrated into the guidance and suggestions that both men gave concerning physical movable-bed and fixed-bed models.

General Distortion Practice at WES

In 1978, Franco wrote a WES instruction report entitled "Guidelines for the design, adjustment and operation of models for the study of river sedimentation problems" (Franco 1978). In that report for the discussion of model distortion, Franco wrote:

> "Principal considerations in the design of movable-bed models should be that the hydraulic forces developed be sufficient to move the material forming the channel bed in simulation of the sediment movement in the prototype and that the model be capable of defining the problem. The horizontal scales that would result in a practical size model based on operation, space, and cost are usually too small to provide the hydraulic forces sufficient to move material of a practical size and specific weight; therefore these forces are obtained by distortion of the linear scales and/or supplementary slope and exaggeration of the discharge and velocity scale relations. Distortion of the linear scales involves the use of a vertical scale ratio larger than the horizontal scale ratio, thus providing greater model depths and slopes."

Additionally, Franco wrote:

> "Because of the effects of model distortion, distortion of the linear scales should be as small as conditions will permit. Use of higher distortion in model linear scales will reduce the initial cost of model construction and space required but will usually increase the time and cost of model adjustment and if not properly handled could have some adverse effects on model results."

Therefore, some of Franco's and Glover's conclusions from the effects of distortion tests were integrated into Franco's report. Specifically, conclusion *c* (effects of higher distortion on the currents) and conclusion *e* (the effects of velocity distortion) were the issues Franco addressed in his instruction report.

In Tables B1 and B2 of the instruction report, Franco presented some scales used in model studies conducted at WES. Table B1 was for sand bed models, and the distortions for the studies listed varied from about 4.2 to 9. Franco later reported additional sand bed model studies with distortions ranging from 6 to 10.83 (Franco 1982). This author conducted other sand bed model studies not listed by Franco with distortions of 8 and 10 (Franco et al. 1970; Pokrefke and Franco 1981). The reason for the high distortions, much higher than the distortion that Franco and Glover felt affected the flow, was the fact that the velocities required to mobilize the sand bed had to be essentially equal to the velocities required to move the prototype channel bed which was composed mainly of sand. In Appendix A of the instruction report, Franco discussed the characteristics of model bed material. Concerning the use of sand as the bed material, Franco wrote:

> "Sand is readily available and has a rather uniform specific gravity of 2.65. It is found in the bed of most alluvial streams regardless of the size of the stream. Smaller streams, in order to compensate for the smaller depths, need steeper slopes to provide the energy required to move the proportional amount of sand as the larger rivers. …The disadvantage of using sand in addition to the greater forces required to be moved than a lighter material is the formation of ripples on the model bed. These ripples have a significant effect on flow, particularly where depths are small. …Ripples not only affect channel roughness in the model but produce irregularities in channel depths. With small vertical scales, the irregularities can be significant and should be balanced to eliminate the high and low points when preparing a map of the bed."

In Table B2 of the report, Franco reported for coal bed models with distortions that varied from 0 to 2.5. This author conducted or was involved in other coal-bed, movable-bed studies over the years with distortions varying from 0 to 4 (Franco and Pokrefke 1983; Derrick et al. 1994). Therefore, the conclusion *c* from the effects of distortion tests for impacts of distortions of 4 and higher was almost universally adhered to at WES for non-sand bed model studies.

Additional Information Relative to Modeling Practices

In 1942, the American Society of Civil Engineers (ASCE) published a manual on Hydraulic Models (ASCE 1942). Concerning distortion of movable-bed models, the manual stated:

> "Movable-bed models are nearly always distorted geometrically, although they should never be so distorted as to affect, appreciably, the accuracy of reproduction of velocity distribution. The simulation of bed

movement is directly dependent upon an accurate reproduction of velocity distribution. It has been found that a distortion of about six is the permissible maximum for movable-bed models, although it is considered desirable to keep the distortion to four or less."

Note that this ASCE manual was published prior to the investigations conducted by Franco and Glover and reported herein.

In 2000, ASCE completely rewrote the 1942 hydraulic models manual (ASCE 2000). In the newer version concerning model distortion the manual stated:

> "Vertical distortion produces flow cross sections that have larger flow depths and greater vertical gradients and should ensure that model flow is turbulent and maintains kinematic similitude (that is, flow-velocity similitude). The price though, is reduced accuracy of geometric and dynamic similitude."

> "Acceptable limits for model distortion in loose-bed modeling are recommended with some hesitancy. Hydraulic modeling, after all, is a means of gaining insight into processes. The more detailed and quantitative the insight required, the stricter that adherence to similitude criteria necessarily must be. The extent of adherence is at the discretion of the modeler, bearing in mind the recipient of the results produced by the model. A survey of loose-bed modeling indicates that most modelers suggest a limit of 6 for vertical distortion. Practical constraints, such as the slope stability of the sediment or particles modeled, may require a lesser value."

The 2000 manual stated that vertical distortion produces various factors for consideration by the modeler. Some of those factors are (a) exaggeration of secondary currents, (b) distortion of eddies, (c) occurrence of flow separation on inclined boundaries, whose slope is increased, where separation would not occur at full scale, (d) a different lateral distribution of flow in the model from the full scale, and (e) the ratios between vertical and horizontal forces at full scale would not be maintained in the model.

Therefore, relative to the conclusions developed by Franco and Glover in their effects of distortion tests, ASCE essentially supported conclusion *b* (concerning flow around bends), conclusion *c* (concerning distortions of 4 or higher), and conclusion *d* (concerning the deflection of currents).

In 1972, Franco published some notes on model techniques that echo what ASCE stated (Franco 1972). Franco noted:

> "…distortion of the linear scales and supplementary slope tend to affect the relationship of velocity, width-depth ratio of the channel and curvature, and consequently tend to affect the distribution of energy within the channel. …Because of these effects, distortion and supplementary slope should be maintained as small as feasible."

In his note, Franco went on to address navigation model studies, which are generally conducted at WES on fixed-bed models. He wrote that "…it is important that these (navigation) models reproduce accurately current directions and velocities, crosscurrents, and eddies that affect navigation, they (navigation models) are undistorted…."

Relative to impacts of model distortion, Glover addressed the issue in a report on river training hydraulic models (Glover 1971). In that report, which was based on general research and site-specific sand bed models, Glover stated highly distorted models (in this case he was addressing distortion factors of 10 and 11.1) could "lead to inaccuracies," and the studies would provide "a general indication of the comparative effectiveness of the proposed plans." At the conclusion of his report, Glover stated that use of "highly distorted scales which were not adjusted to the point where they gave detailed reproduction of prototype conditions" should have these limitations taken into account in the evaluation of the model results.

Due to the high distortions inherently required to conduct sand bed models, WES eventually eliminated such studies in the late 1970s. From that point forward, all physical movable-bed models were conducted using coal bed models regardless of which particular river, small or large, was under investigation. However, even before that time, the vast majority of WES movable-bed studies were conducted on coal bed models. In fact some of the earliest movable-bed studies conducted at WES were coal bed studies. The Dogtooth Bend, Mississippi River model was conducted in 1936 using coal (USAEWES 1938). This study had a distortion of 6.

In a book by Murphy (Murphy 1950), it was stated in describing riverine erosion and sedimentation processes using physical models, that the bed material should have "a comparatively (relative to the prototype) low specific gravity." Murphy stated that the movable-bed material cannot be geometrically scaled since the resulting material particles would be "so small that they are held in suspension in the fluid instead of settling." Murphy concluded saying: "Current practice favors lightweight bed material. In general, the final configuration of the stream bed in a properly designed model may be expected to agree with the prototype, but conformation tests should be made whenever possible." Besides WES, other Corps of Engineers hydraulic facilities also used lightweight bed material. The North Pacific Division Hydraulic Laboratory located at Bonneville, OR, used coal in its movable-bed models; while the Mead Hydraulic Laboratory in the Missouri River Division at Mead, NE, used ground walnut shells.

Author's Comments

This author conducted or was involved in physical, movable-bed model studies at WES for about 35 years. The vast majority of those models included curvilinear flow and only a very few were straight modeled reaches. Therefore, I base my comments on the models that included bendways within the modeled reach and which link closely to the effects of distortion investigations conducted by Franco and Glover.

Relative to the conclusions that Franco and Glover made from their investigations, this author has the following comments.

a. Conclusion *a*: Negligible distortion effects in straight reaches is reasonable since the flow is essentially straight downstream and any variation would be a result of the turbulence in the model. This author had limited experience in researching straight, prototype sites although the few that were studied were conducted in movable-bed models having distortions of 3 or less. However, in a riverine reach including training structures such as dikes, this conclusion may not be valid.

b. Conclusion *b*: The data presented indicate this is a significant result of the research, and apparently significantly influenced the guidance that Franco and Glover provided to their staff over the years.

c. Conclusion *c*: Again, the data support the impacts to curvilinear flow at the higher distortion values. Maintaining distortions in WES models below a value of 4, except in the case of sand bed models, was guidance that Franco and Glover consistently provided over the years.

d. Conclusion *d*: Over the years, particularly on sand bed models, the deflection of currents in bendways often caused the greatest problem during model adjustment/calibration. Such was not the case on coal bed models with significantly less distortion, although the helical flow was still observed in those types of models.

e. Conclusion *e*: The data presented support this conclusion. Observations by this author on movable-bed models using various horizontal and vertical scales where the discharge scale was exaggerated over the Froudian relationship to obtain bed material movement and stage was varied based on prototype stage-discharge relationships, support this conclusion.

f. Conclusion *f*: The specific tests addressing increased roughness only partially support this conclusion. There is further discussion of this issue later in the discussion of Froude numbers. Although limited mostly to observations of the WES Mississippi Basin Model and certain estuarine physical models with roughness strips added, adding roughness can help reduce the effects of distortion. The one controlling factor here is that it is only applicable on fixed-bed models and not on movable-bed models.

In conducting physical, movable-bed models, as they related to linear distortion, the following were followed or observed:

a. On coal bed models, the linear scale distortions used were 4 or less with the vast majority having distortions of 2.5 or less.

b. On sand bed models, the linear scale distortions were always greater than 4, which was required to provide enough energy in the flow to move the sand grains in the model.

c. On sand bed models, the higher distortions created significant impacts to the flow distribution and required much greater effort, compared to coal bed models, to ensure that the entrance conditions reasonably replicated prototype conditions.

d. Helical or spiral flow has been documented in physical models having linear-scale distortions of 0, 2.4, and 4.

e. The importance of replicating the prototype flow velocity distribution cannot be overstated. Franco, Glover, and ASCE emphasized the critical need to maintain flow distribution. Guidance that Franco (Franco 1978) and Glover gave over the years to this author was addressed and the importance of maintaining the flow distribution over the full range of stages and discharges used in model testing.

f. The use of distorted models should be avoided on studies that require accurate reproduction of flow velocities and direction. To this author's knowledge, WES conducted all navigation model studies using only undistorted physical fixed-bed or semi-fixed-bed models.

g. The use of distorted fixed-bed models with the addition of channel roughness elements is applicable in studies where some variation of the velocity distribution or the path of travel is acceptable. An excellent example of such a model was the WES Mississippi Basin Model (MBM), which had a distortion of 20 (see USAEWES 1942), and was capable of accurately reproducing the relationship between stages and discharges and the travel time of flood waves. On this model, deviation from the Froudian relationships were thoroughly investigated and considered in the model results.

In the discussion of the velocity cross sections for the Plan A, Series 1 tests, Franco and Glover stated "comparison of the velocity distribution for the various models downstream of the bend indicated very little significance in differences" (see Chapter 4). This author concluded that there were differences in this data, which may or may not be considered significant. By inspection of Plates 33 through 43, this author came up with the following conclusions concerning the velocity cross sections:

a. In the straight reach upstream of the bend, the thread of maximum velocity tended to vary in location within the channel as the distortion increased.

b. The greatest variation in the measured maximum velocity occurred in the straight reach upstream of the bend.

c. In the straight reach upstream (sta 20+00 to 40+00) and downstream (sta 90+00 to 190+00) of the bend, the highest maximum velocity occurred at the 2-distortion.

d. In the bend (sta 40+00 to 71+41.6), the maximum velocity tended to remain located on the right side of the channel for all distortions, but the isovel tended to move toward the water surface as distortion increased.

e. In the bend, the highest maximum velocities tended to occur at the higher (8- and 10-) distortions.

f. In the straight reach downstream of the bend, the lowest maximum velocity tended to occur at the higher (8- and 10-) distortions.

g. In the portion (sta 130+00 to 190+00) of the channel downstream of the bend, the smallest variation in the measured maximum velocity occurred.

One hydraulic parameter which neither Franco nor Glover addressed was Froude number. To better understand the Froude numbers in which the tests they conducted were operating, Table 6 was prepared by this author.

Table 6
Computed Froude Numbers

Condition/Series	Tests	Distortion Factor or Scheme[1]	Froude Number
Prototype			0.249
Plan A, Series 1	All Tests	0, 2, 4, 6, 8, & 10	0.249
Plan A, Series 2[2]	1 - 3	0, 2, 3, & 4	0.249
Plan A, Series 2[2]	7	1-A, 1-B, 1-C, & 1-D	0.249, 0.176, 0.144, & 0.125
Plan A, Series 2[2]	8	2-A, 2-B, 2-C, & 2-D	0.125, 0.249, 0.353, & 0.498
Plan A, Series 2[3]	4 - 6	2, 3, & 4	0.249
Plan A, Series 2[3]	10	1-B, 1-C, & 1-D	0.176, 0.144, & 0.125
Plan A, Series 2[3]	9	2-A, 2-B, & 2-C	0.125, 0.249, & 0.353

[1] Scheme is shown on Plan A, Series 2, Tests 7, 8, 9, and 10 (Plates 47, 48, 53, & 52).
[2] Manning's n for these tests was 0.012.
[3] Manning's n for these tests was 0.025.

Relative to Froude numbers and the various tests conducted to determine the effects of distortion, the following comments are presented by this author:

a. For all of the Plan A, Series 1 tests; Plan A, Series 2, Tests 1 through 3; and Plan A, Series 2, Tests 4 through 6, the Froude number was identical to the prototype and the differences in the various test results were strictly a function of the amount of distortion. Therefore, for models having equal model and prototype Froude numbers, Franco's and Glover's conclusion that model distortions of 4 or higher affected the current directions downstream of a bend is a significant finding.

b. Based on the results of Plan A, Series 2, Tests 1 through 3 (Manning's n of 0.012) and Tests 4 through 6 (Manning's n of 0.025), the influence of channel roughness on surface currents was dramatic. In Tests 1 through 3 (Plates 44 through 46), there was a significant shift in the currents as the distortion factor changed from 0 to 4 up to the point in Test 2 for the 3- and 4-distortions when the float was released upstream of the bend where the left wall was apparently limiting the currents. The left wall also appeared to limit the surface currents in Test 3 for the 2-, 3-, and 4-distortions when the float was released upstream of the bend. In Tests 4 through 6 (Plates 49 through 51), as the flow passed through the bend the magnitude of the current shift decreased significantly with the higher channel roughness (compare the bottom of Plates 44 and 49 and 45 and 50). However, when the surface float was released 600 ft (prototype) from the right wall at sta 80+00, the additional channel roughness appeared to have little effect on the surface currents (compare the bottom of Plates 46 and 51). Therefore, for models having equal model and prototype Froude numbers, Franco's and Glover's conclusion that increasing the channel roughness tended to reduce the effects of distortion is limited.

c. For Plan A, Series 2, Tests 8 and 9 (Plates 48 and 53), where the depth was held constant and the Froudian velocity scale was varied, the Froude number (and velocity) varied by a factor of about 4 (a factor of 2 relative to the prototype Froude number) and a factor of about 3 (a factor of 1.4 relative to the prototype Froude number), respectively. However, the surface currents varied very little in these tests. In the analysis of Test 8 (see page17), Glover concluded, “varying the velocity scale, as is often required in movable-bed models to obtain bed movement, would have only a small effect on current directions and flow distribution.” However, this statement should be taken in the context that the tests were conducted with Froude numbers up to twice the prototype and not greater than that. As Glover stated, the schemes used in these tests are similar to the procedures followed on WES coal bed, movable-bed models in that the velocity scales are exaggerated for the low stages/discharges and as the stage/discharge increases the amount of model discharge exaggeration, relative to the Froudian relationship, decreases. Therefore, at the higher model stages/discharges, WES models generally used a value close or equal to the Froudian relationship. Referring to Franco 1978, Figure 2 gave an example of a coal bed model discharge relationship curve for a model having a horizontal scale of 1:120 and a vertical scale of 1:80. For such a model, the Froudian discharge relationship would be 1:85,865. From Figure 2, prototype discharges of 20,000 and 700,000 cfs had discharge scales of 1:32,000 and 1:90,000, respectively. Therefore, the lower discharges (and corresponding stages) had a flow exaggeration between two and one-half to three times the Froudian relationship, while the highest discharge (and corresponding stage) had essentially no flow exaggeration.

d. Based on Plan A, Series 2, Tests 8 and 9, the results appear to indicate that Froude number distortion above the prototype value as it is determined relative to the vertical scale and corresponding velocity scale should be maintained at about a factor of 2. Once the Froude number exaggeration exceeds that value, the velocity has reached a point that the current patterns are no longer influence by the channel bed roughness. This is probably strictly a result of the fact that the channel velocities reach a point that they are moving so fast that they are not influenced by the channel roughness and as such cannot spread or diverge to the degree they would at the prototype Froude number.

e. In Plan A, Series 2, Tests 7 and 10 (Plates 47 and 52), which were held to a constant velocity scale of 1:20, results indicated that the higher roughness (Test 10) tended to reduce the spreading of the surface currents much more than the lower roughness (Test 7). Therefore, in both tests, as the model Froude number decreased, the surface currents tended to spread toward the left wall with that spreading being greater as the Froude number decreased. Perhaps this was the point that Franco and Glover were trying to convey when they stated that increasing the model roughness as the distortion increased tended to reduce the effect of distortion.

f. Addressing Franco's analysis relative to centrifugal force (see Chapter 5), his conclusion was that the effects of distortion could be reduced if the centrifugal force and resulting flow pattern in a distorted model reproduced the prototype. Assuming a distorted model with a horizontal scale of 1:400 and a vertical scale of 1:100, and using Equation 6, the model would have a velocity scale of 1:40 for equal centrifugal forces. However, in such a distorted model the computed Froude velocity scale would be 1:10. Therefore, to maintain similarity of centrifugal forces between model and prototype, as Franco suggested, the velocity scale in the 4-distortion model should be one-fourth of the computed Froude velocity scale. Plan A, Series 2, Test 8, scheme 2-A had a Froude velocity scale, one-half of the computed Froude velocity scale, and there was essentially no difference between the surface currents of that scheme compared to scheme 2-B, which was conducted at the Froude velocity scale.

g. Many of the findings, although somewhat limited at times for fixed-bed models, are significant and add to the knowledge of the effects on distortion. In conducting physical, movable-bed models, where adjustment of channel roughness is virtually eliminated, the modeler should take these findings into consideration during their model design, adjustment, and verification to ensure that the required model distortion stays within acceptable limits.

Closing Comments

The research conducted by John Franco and Ed Glover provides firm evidence on limiting model distortion to less than 4 on riverine physical, movable-bed models using lightweight bed materials. Exceptions to this would be sand bed models, certain flood-control models similar to the MBM, and estuarine models. Their research provides definitive impacts when the 4-distortion limits are exceeded and additionally provides no hope on movable-bed models to reduce those impacts by adjustment of the channel roughness.

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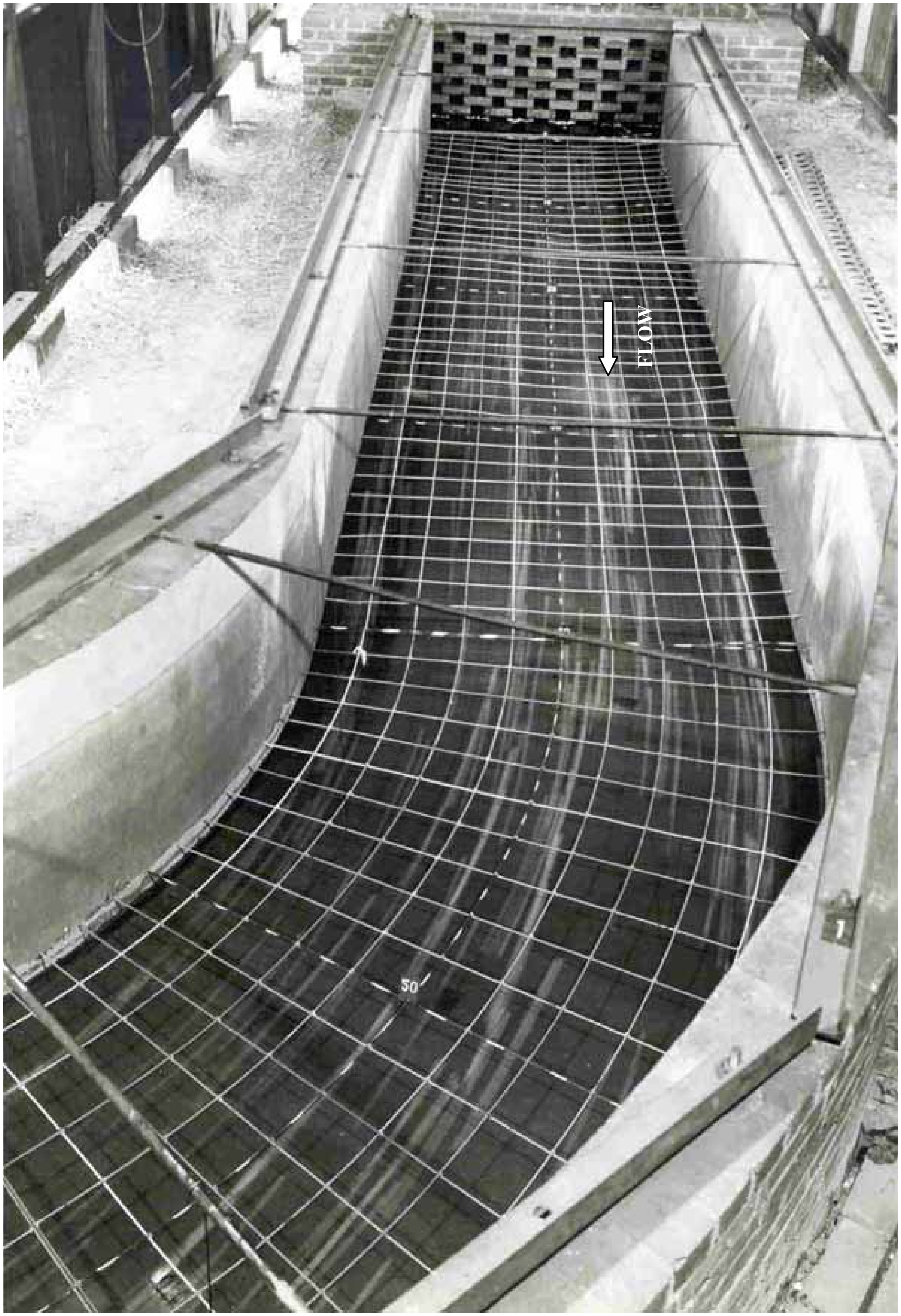


Photo 1. Surface current directions upstream from bend, 0 distortion

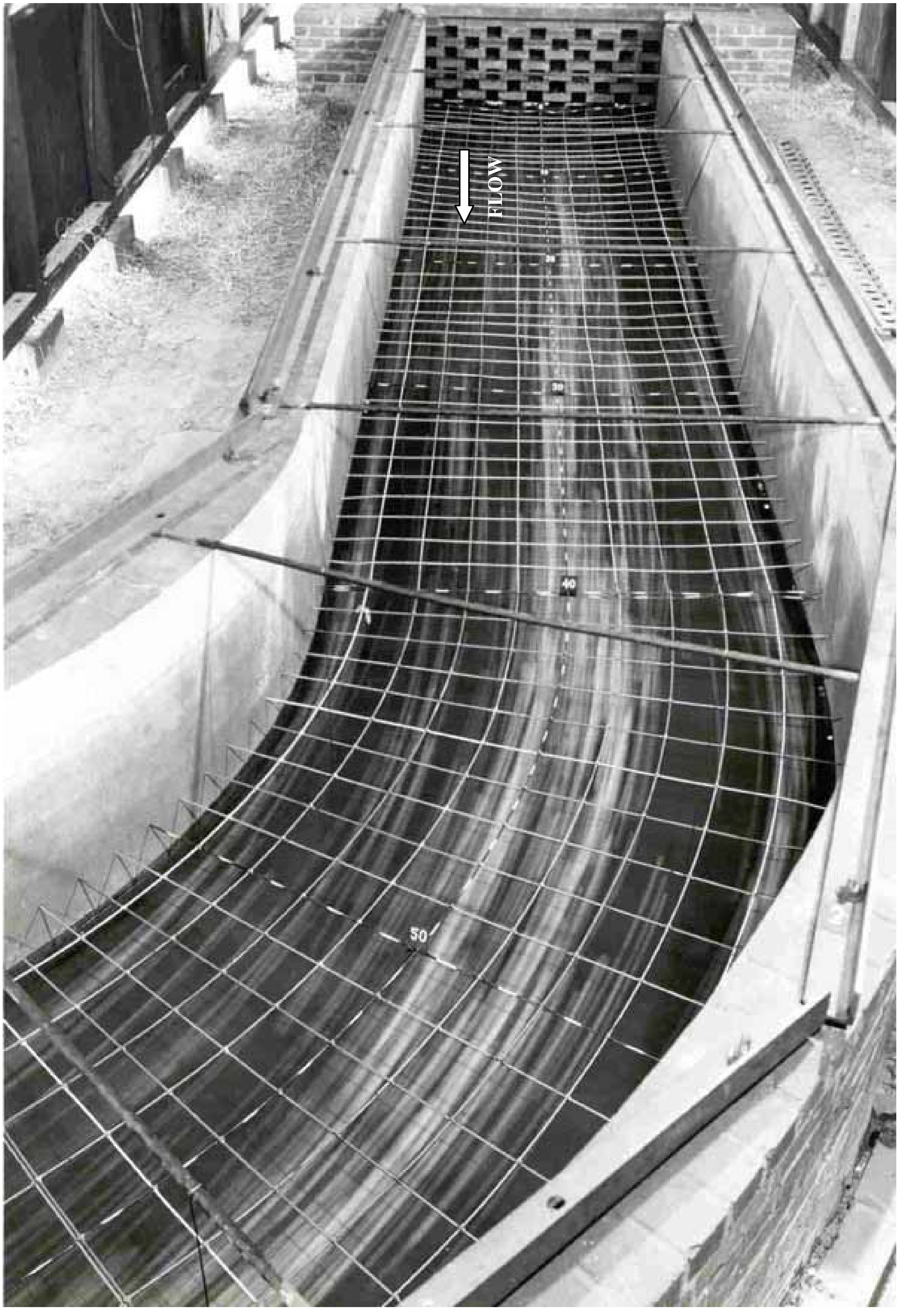


Photo 2. Surface current directions upstream from bend, 2 distortion

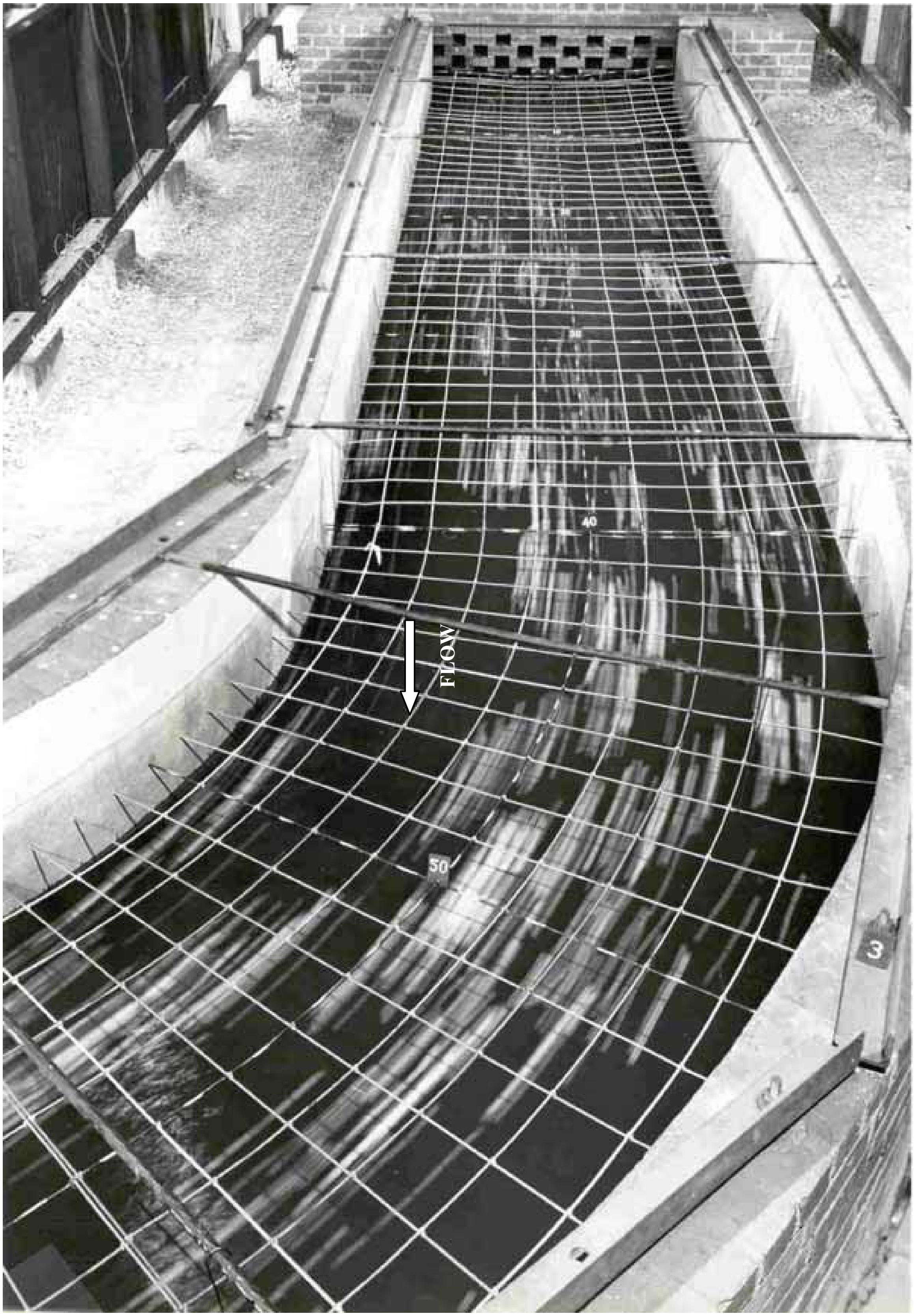


Photo 3. Surface current directions upstream from bend, 6 distortion

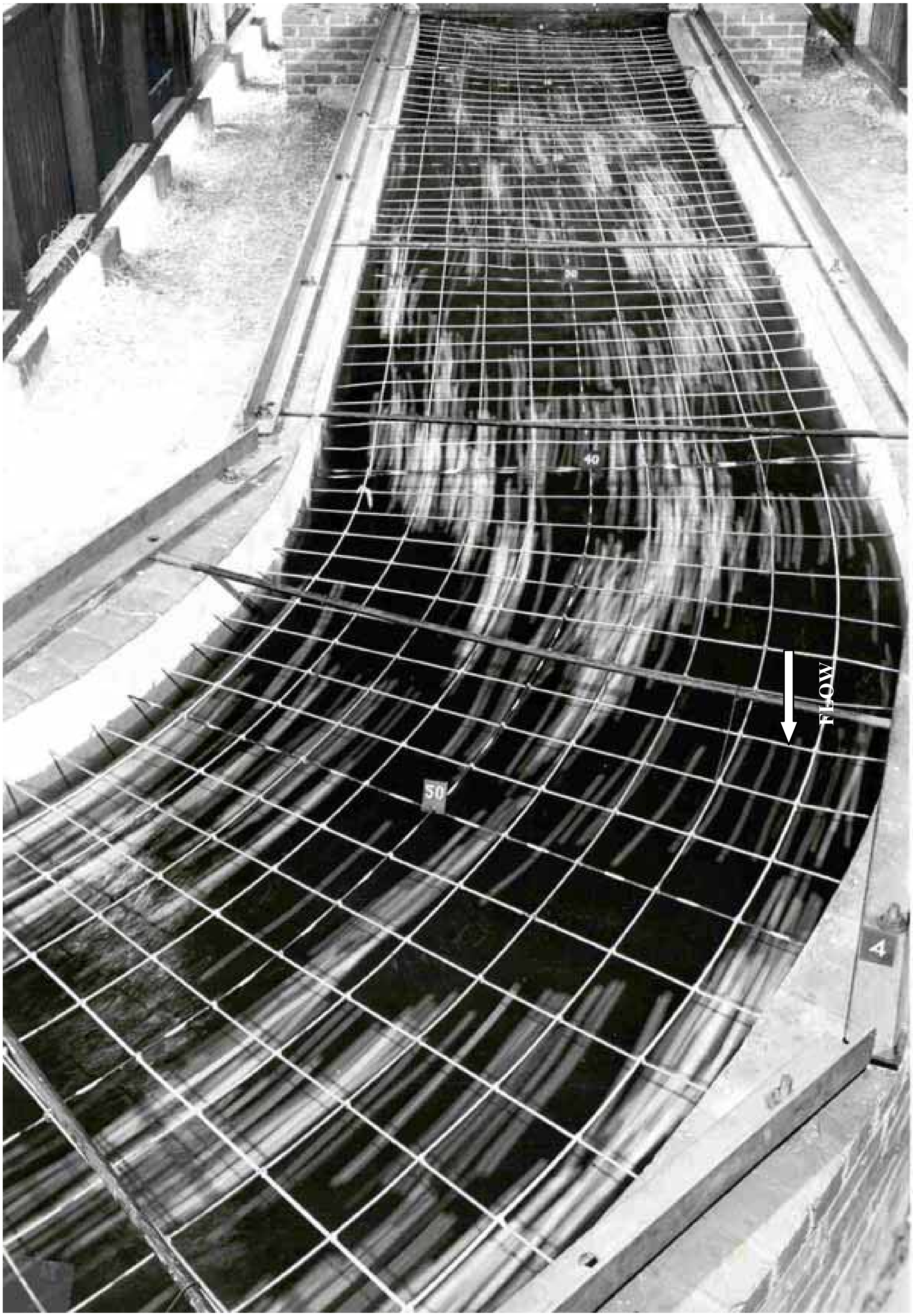


Photo 4. Surface current direction upstream from bend, 10 distortion

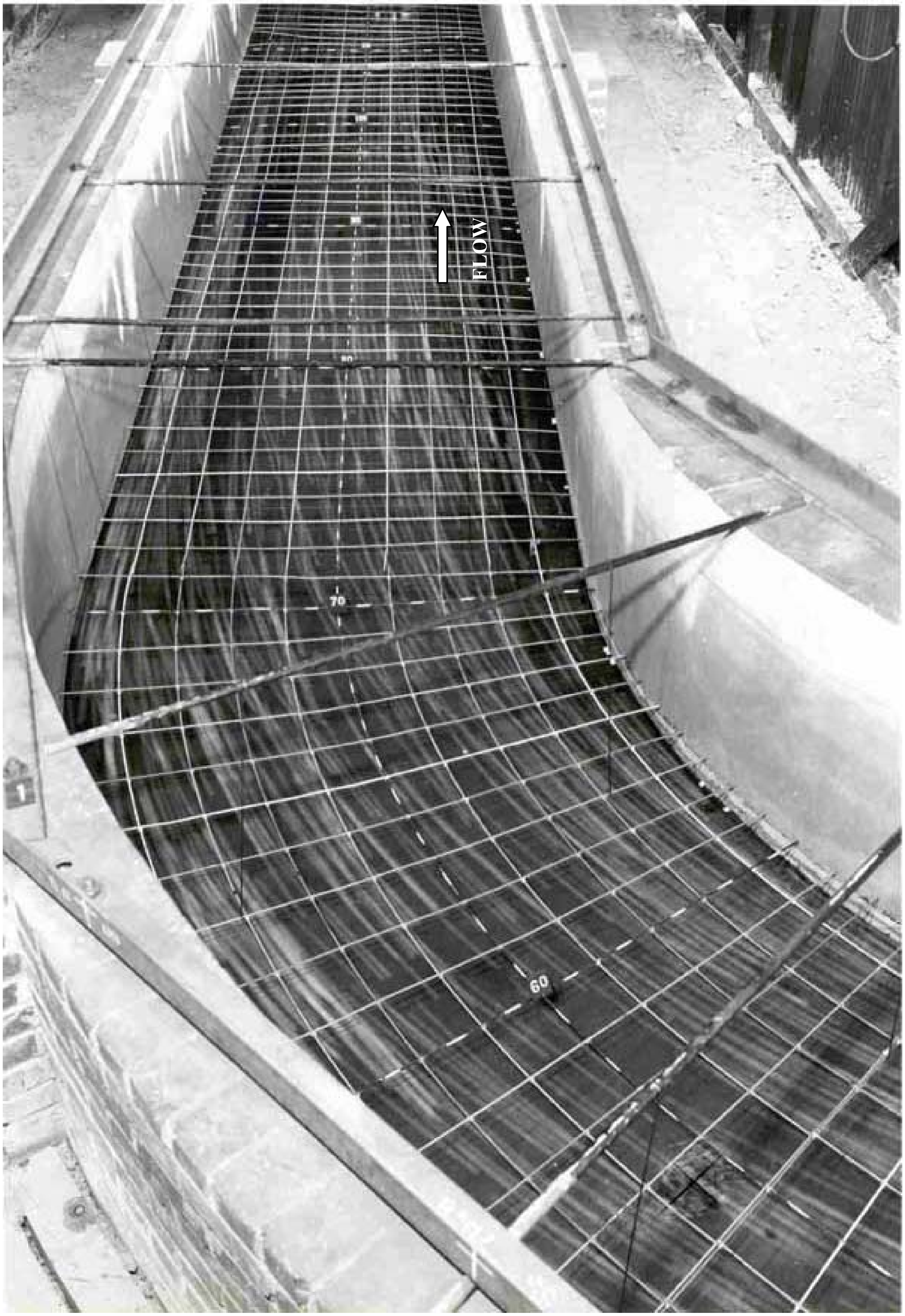


Photo 5. Surface current directions downstream from bend, 0 distortion

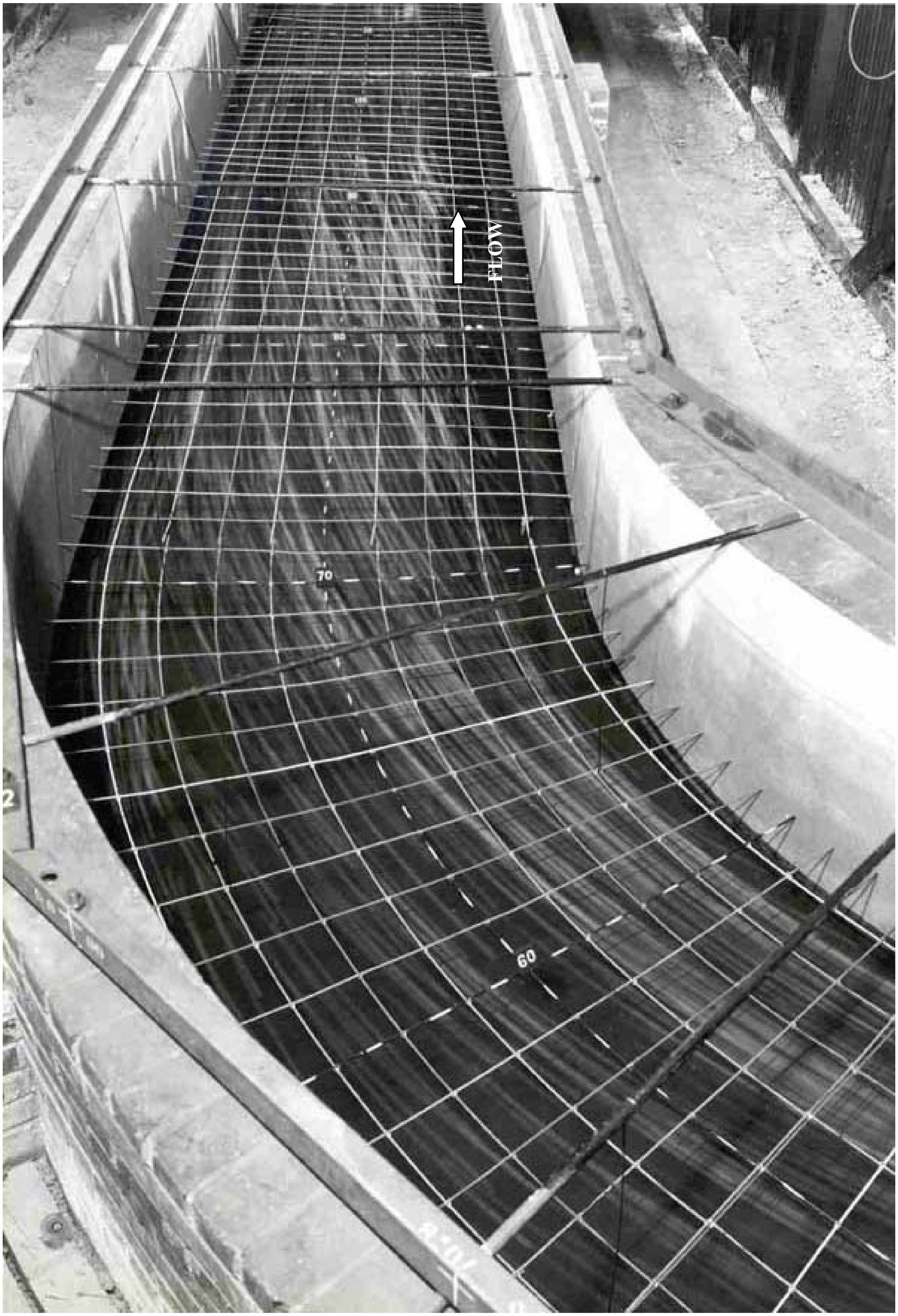


Photo 6. Surface current directions downstream from bend, 2 distortion

Photo 7. Surface current directions downstream from bend, 6 distortion

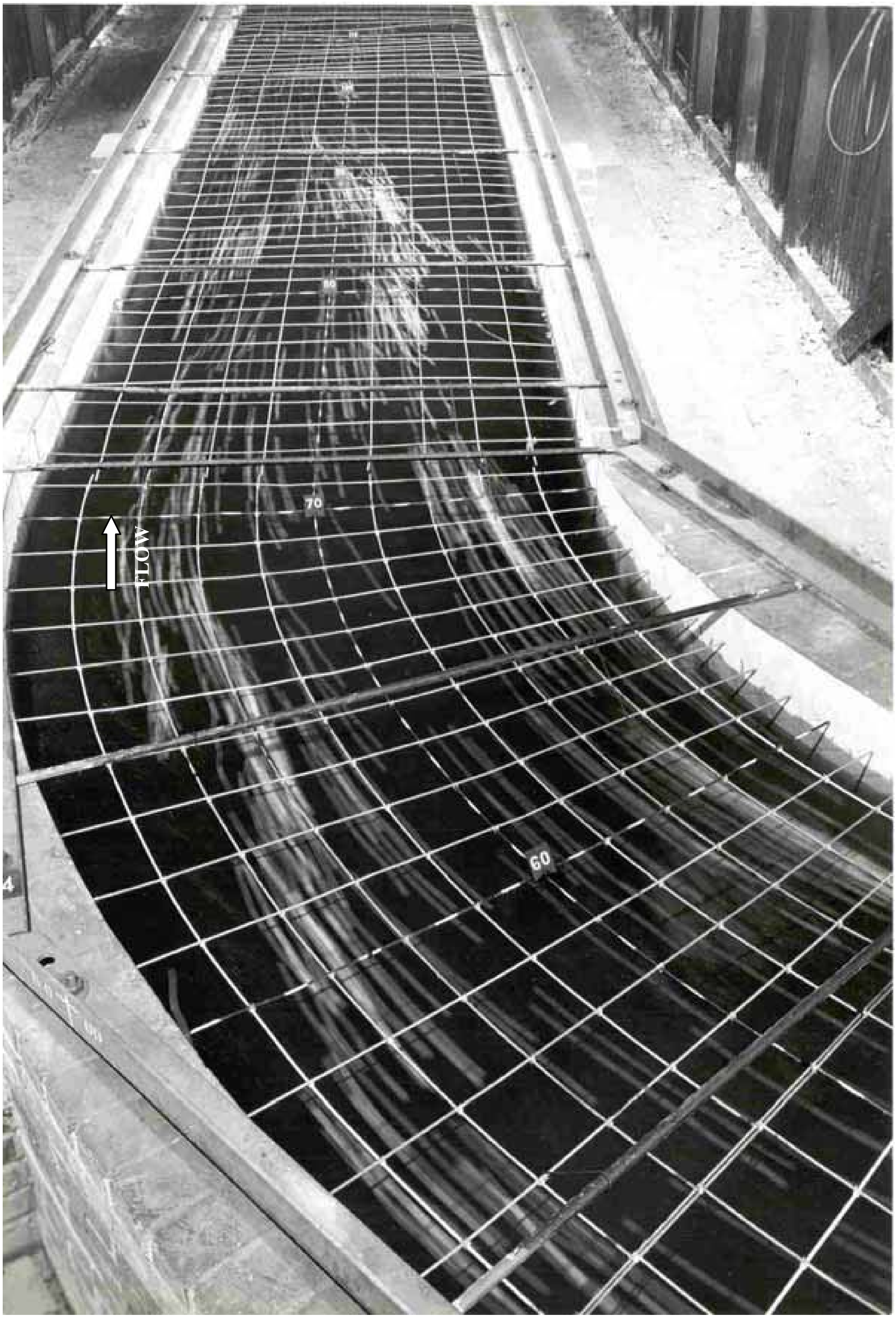
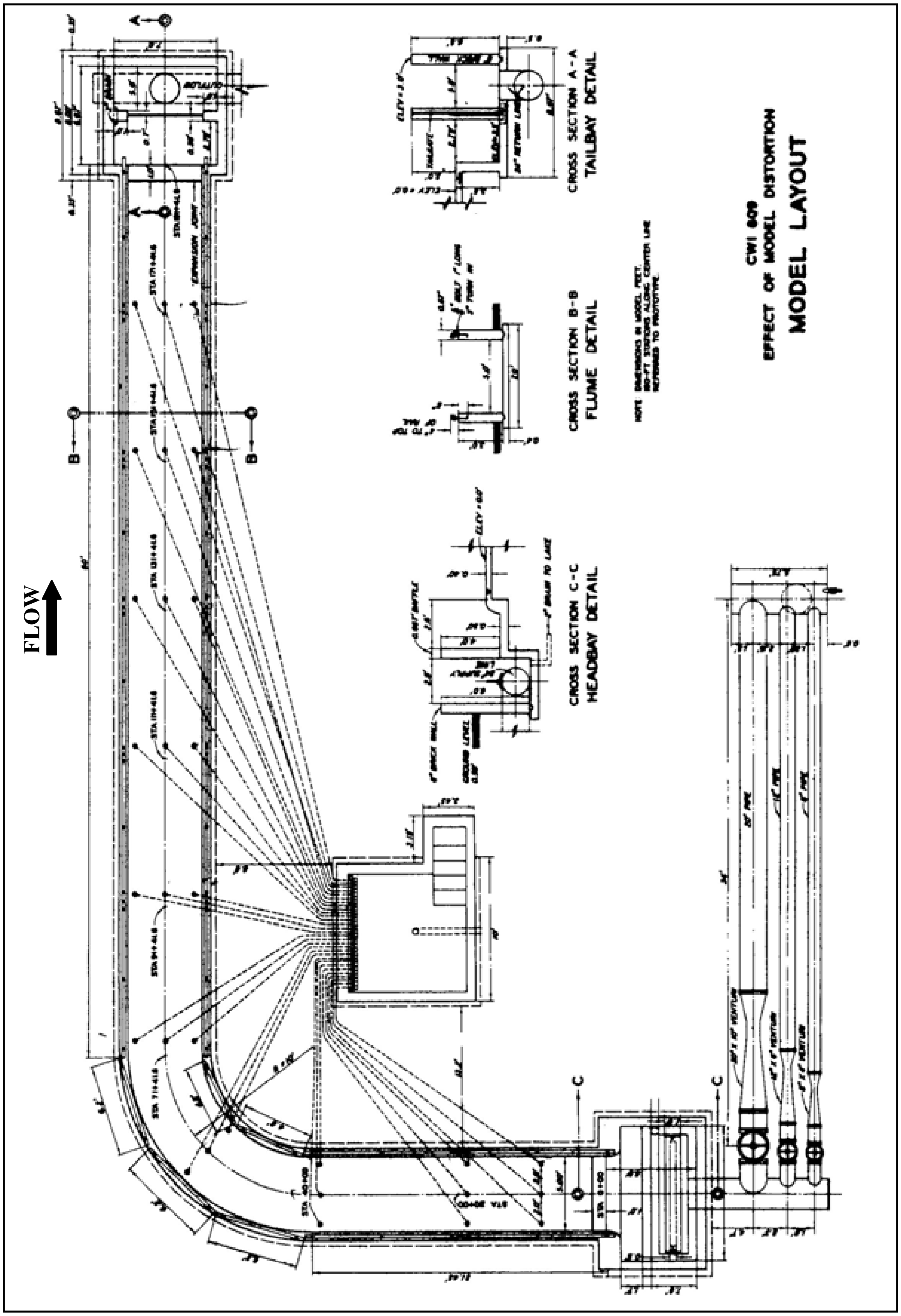
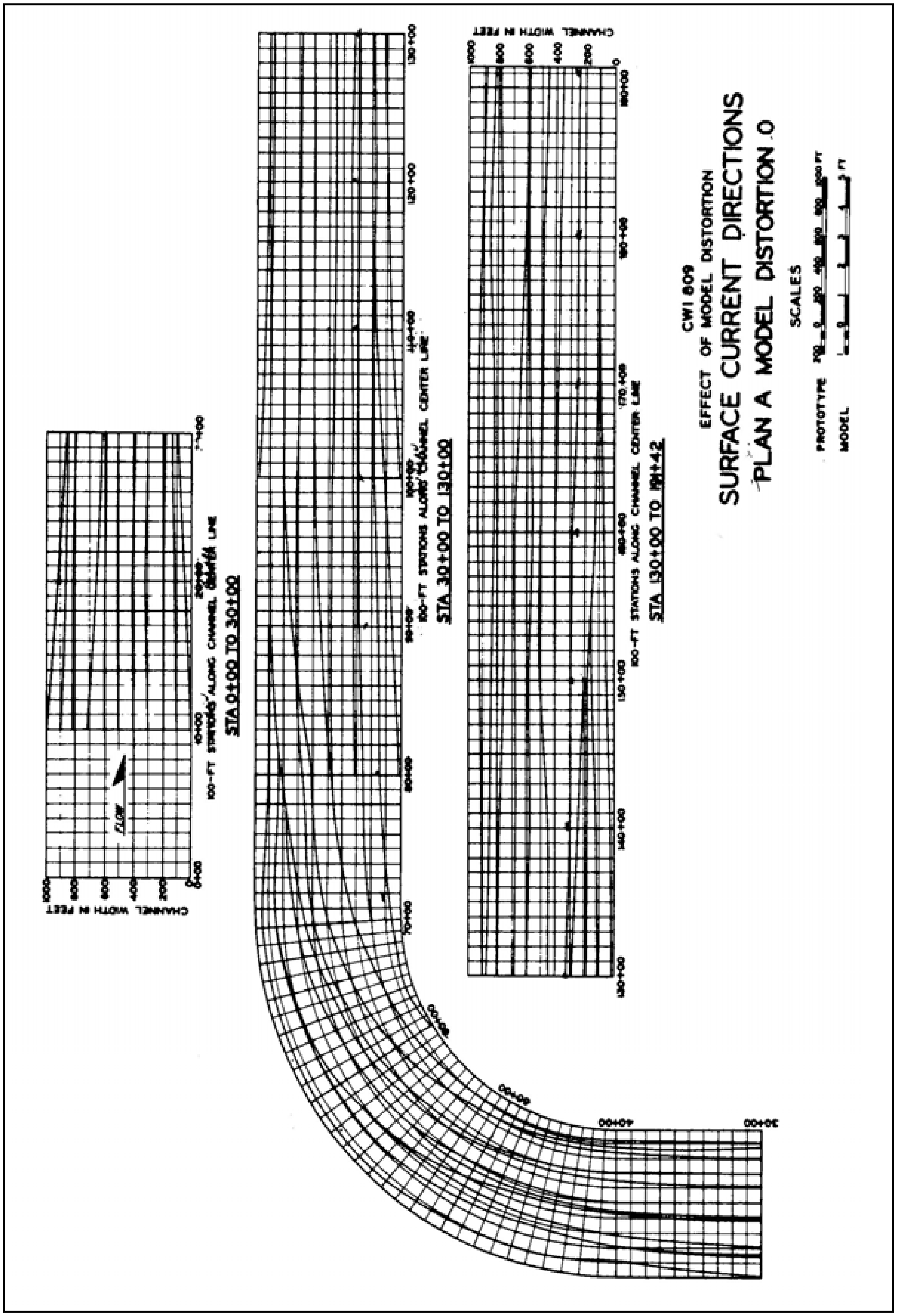


Photo 8. Surface current directions downstream from bend, 10 distortion


FLOW
CROSS SECTION A-A
TAILBAY DETAIL
CROSS SECTION B-B
FLUME DETAIL
CROSS SECTION C-C
HEADBAY DETAIL
CWI 809
EFFECT OF MODEL DISTORTION
MODEL LAYOUT



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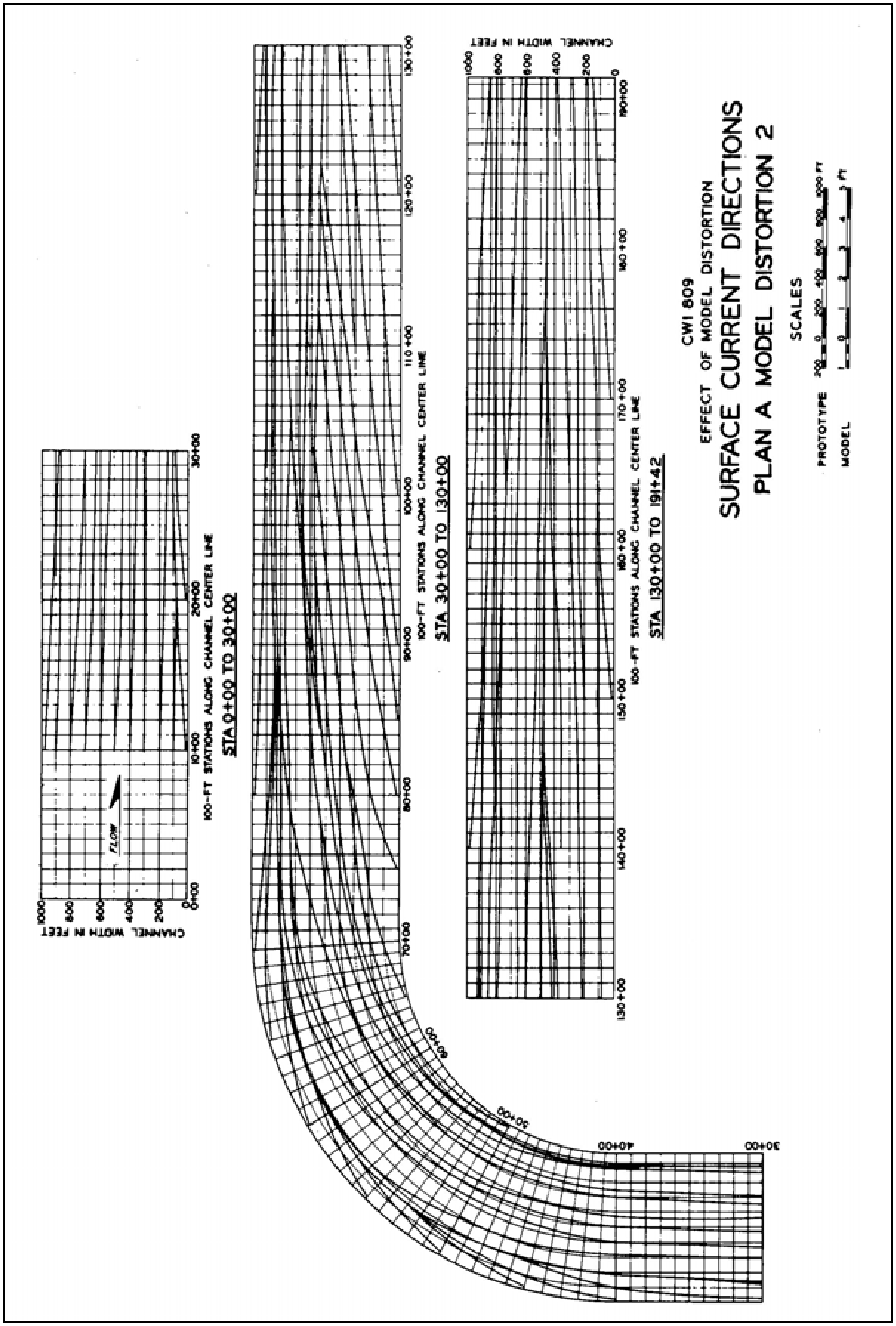
EFFECT OF MODEL DISTORTION
SURFACE CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 0
SCALES
PROTOTYPE
MODEL
FLOW
CHANNEL WIDTH IN FEET
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 0+00 TO 30+00
STA 30+00 TO 130+00
STA 130+00 TO 191+42

Plate 2


CWI 809
EFFECT OF MODEL DISTORTION
SURFACE CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 2
SCALES
PROTOTYPE
MODEL
STA 0+00 TO 30+00
STA 30+00 TO 130+00
STA 130+00 TO 191+42
100-FT STATIONS ALONG CHANNEL CENTER LINE
CHANNEL WIDTH IN FEET
FLOW

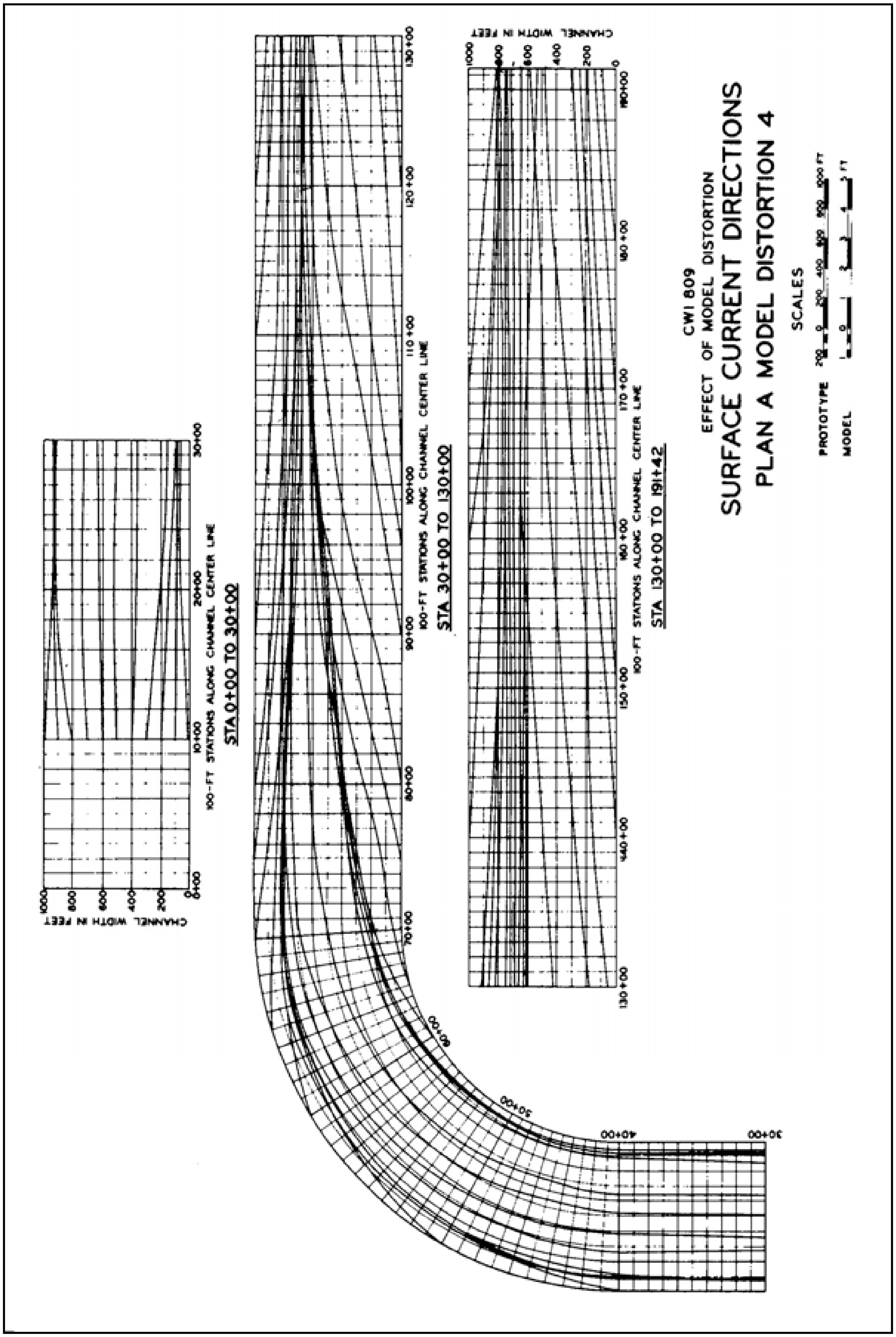
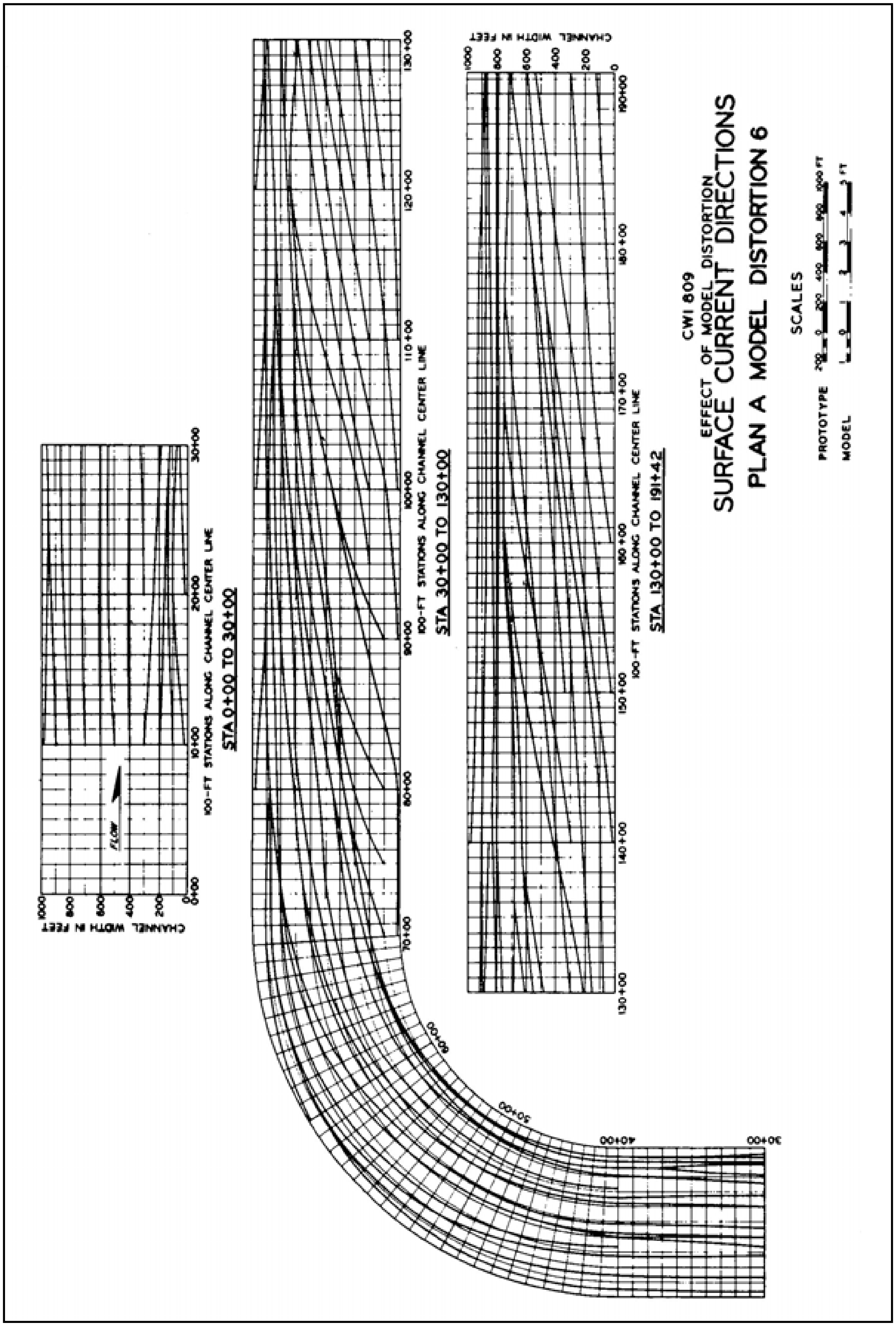
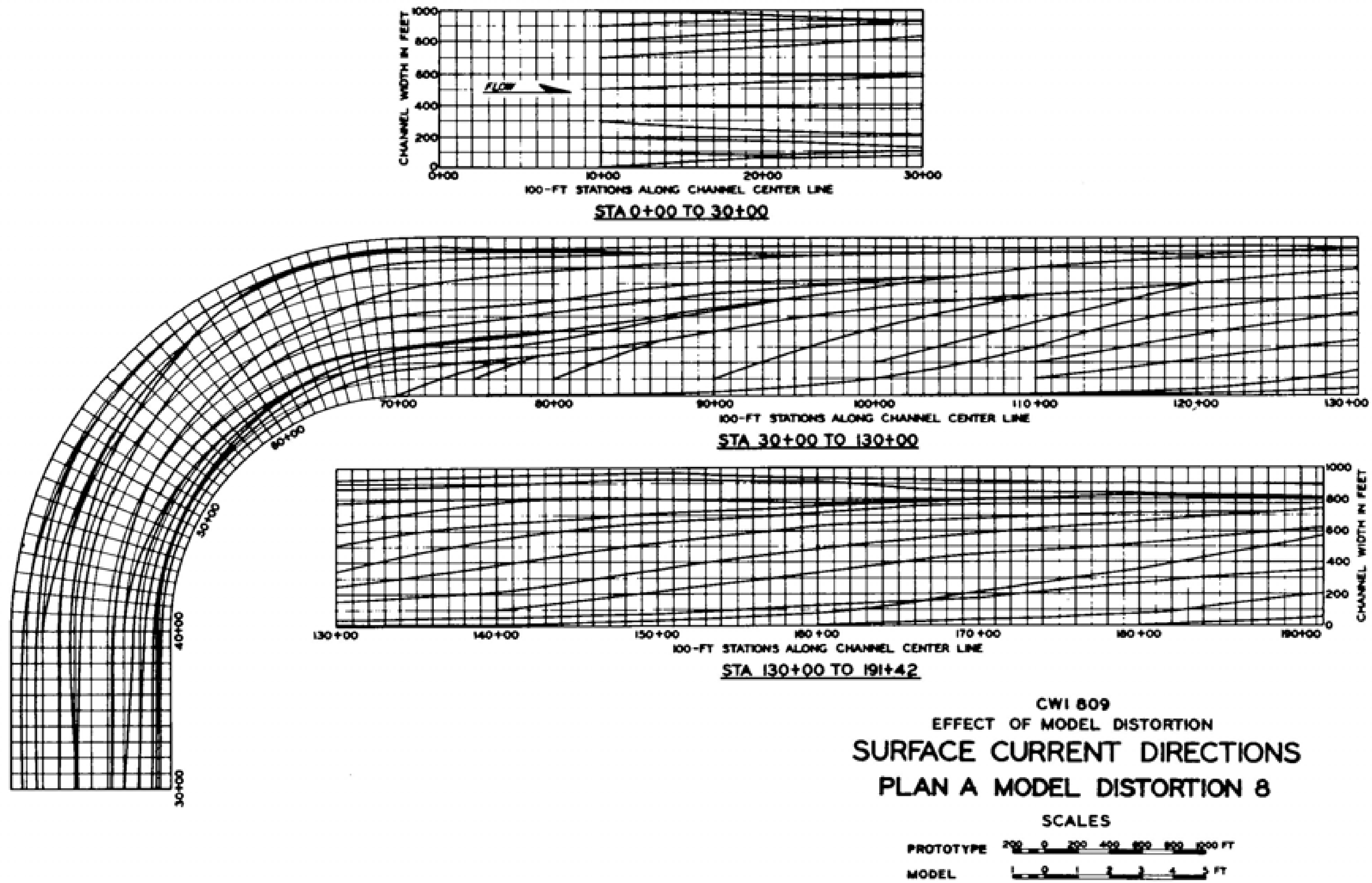

CWI 809
EFFECT OF MODEL DISTORTION
SURFACE CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 4
SCALES
PROTOTYPE
MODEL
STA 0+00 TO 30+00
100-FT STATIONS ALONG CHANNEL CENTER LINE
CHANNEL WIDTH IN FEET
STA 30+00 TO 130+00
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 130+00 TO 191+42
100-FT STATIONS ALONG CHANNEL CENTER LINE
CHANNEL WIDTH IN FEET

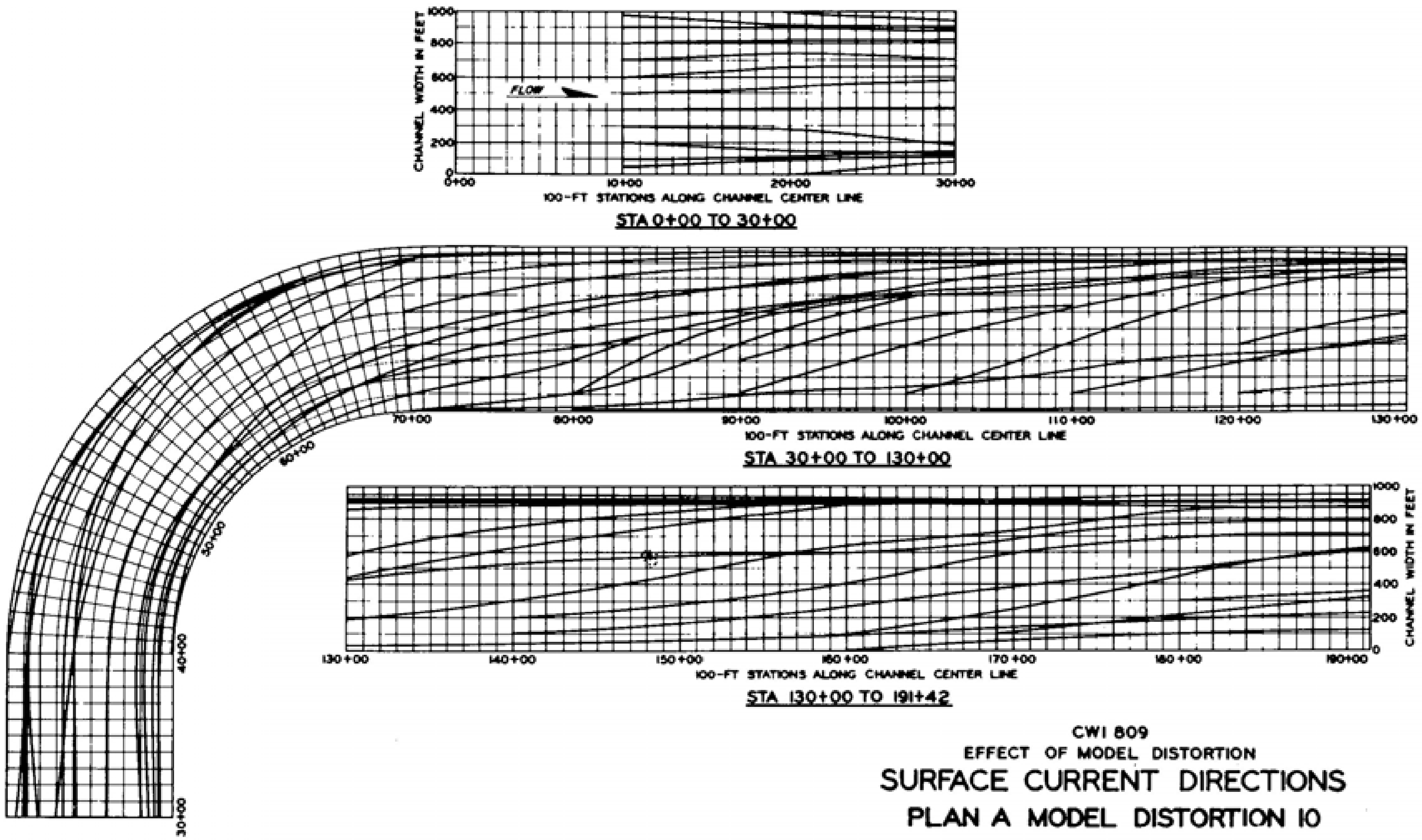
Plate 4


CWI 809
EFFECT OF MODEL DISTORTION
SURFACE CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 6
SCALES
PROTOTYPE
MODEL
STA 0+00 TO 30+00
STA 30+00 TO 130+00
STA 130+00 TO 191+42
100-FT STATIONS ALONG CHANNEL CENTER LINE
CHANNEL WIDTH IN FEET
FLOW



FLOW
CHANNEL WIDTH IN FEET
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 0+00 TO 30+00
STA 30+00 TO 130+00
STA 130+00 TO 191+42
CWI 809
EFFECT OF MODEL DISTORTION
SURFACE CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 8
SCALES
PROTOTYPE
MODEL

Plate 6



CWI 809
EFFECT OF MODEL DISTORTION

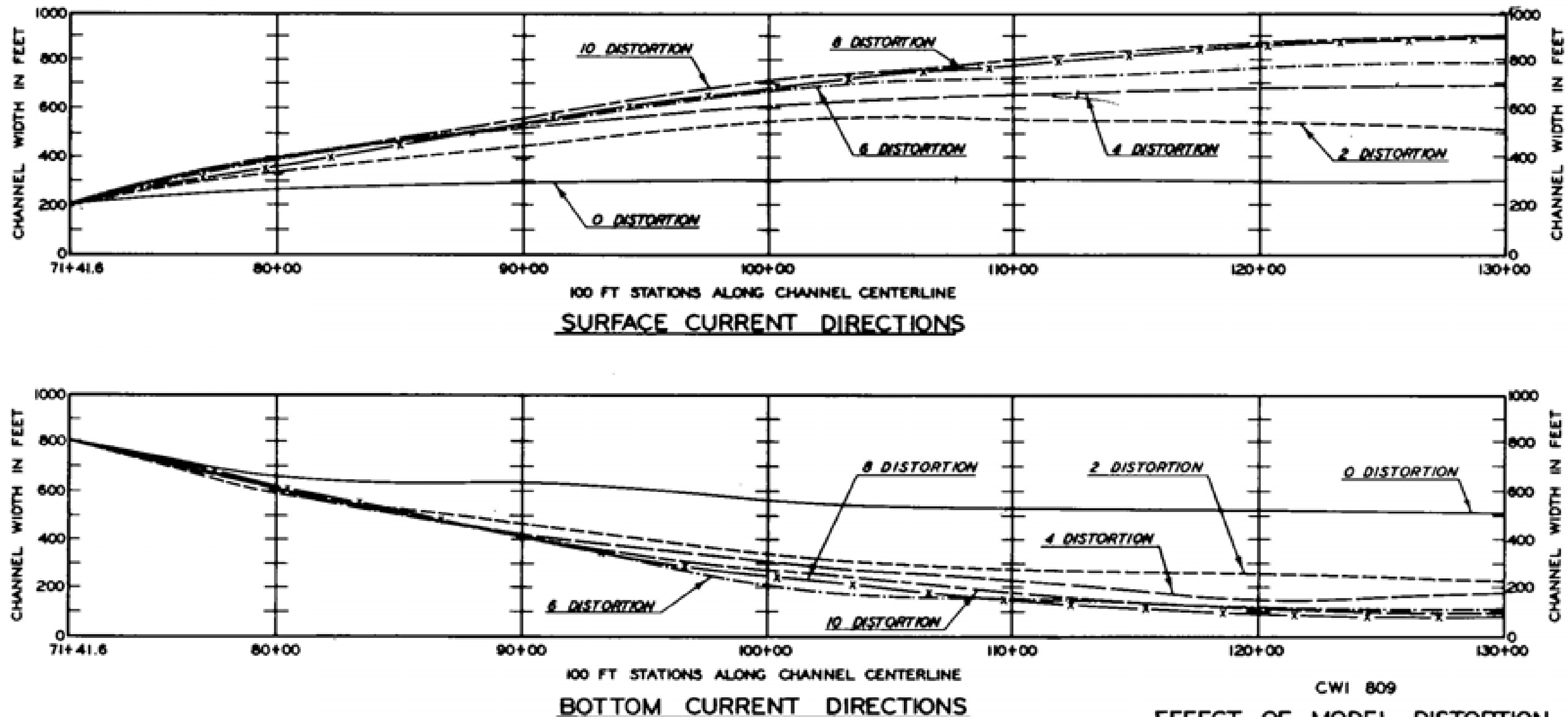
SURFACE CURRENT DIRECTIONS

PLAN A MODEL DISTORTION 10

SCALES

PROTOTYPE 200 0 200 400 600 800 1000 FT

MODEL 1 0 1 2 3 4 5 FT



CWI 809

EFFECT OF MODEL DISTORTION

EFFECT OF DISTORTION ON CURRENT DIRECTIONS

PLAN A

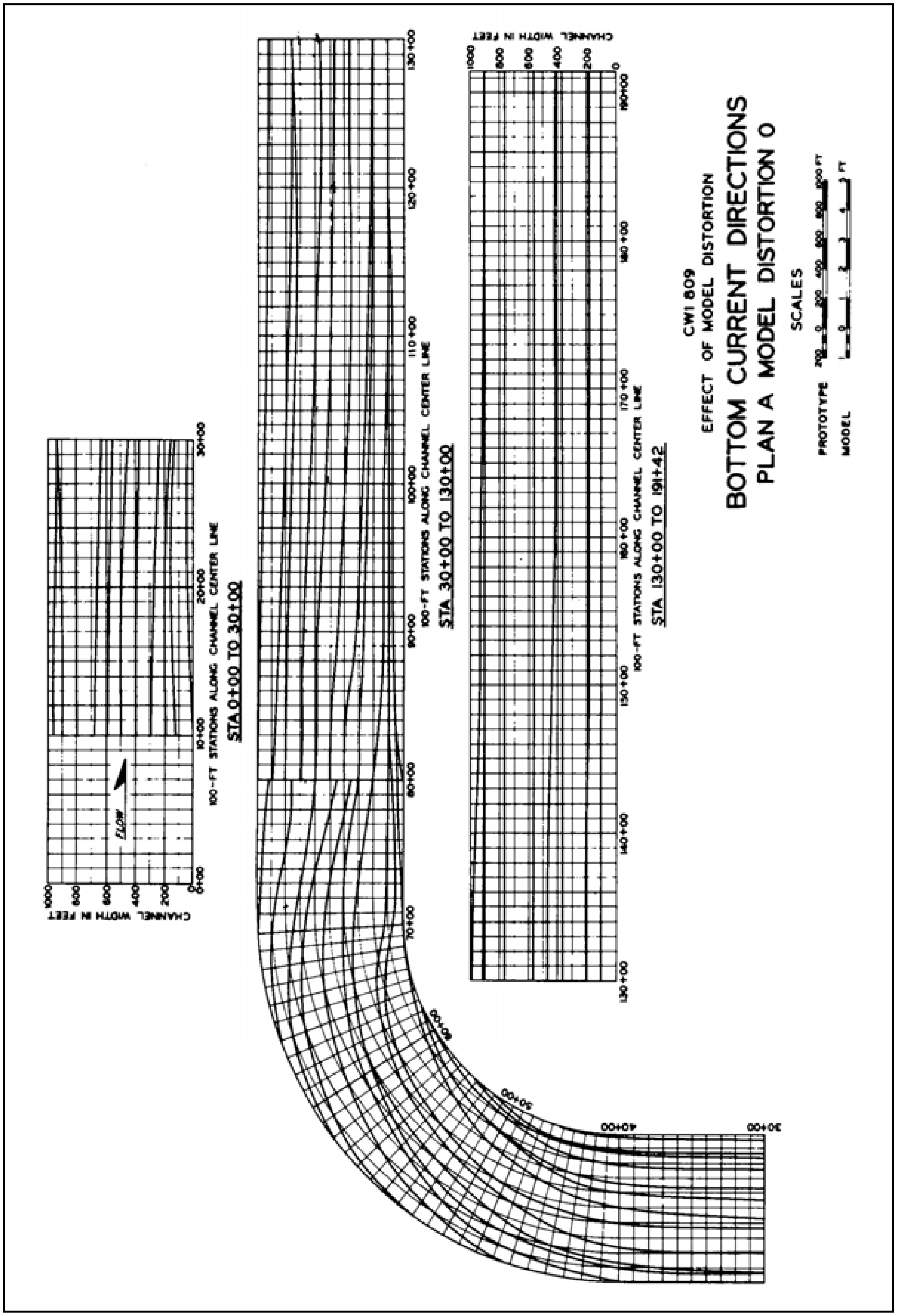
SCALES

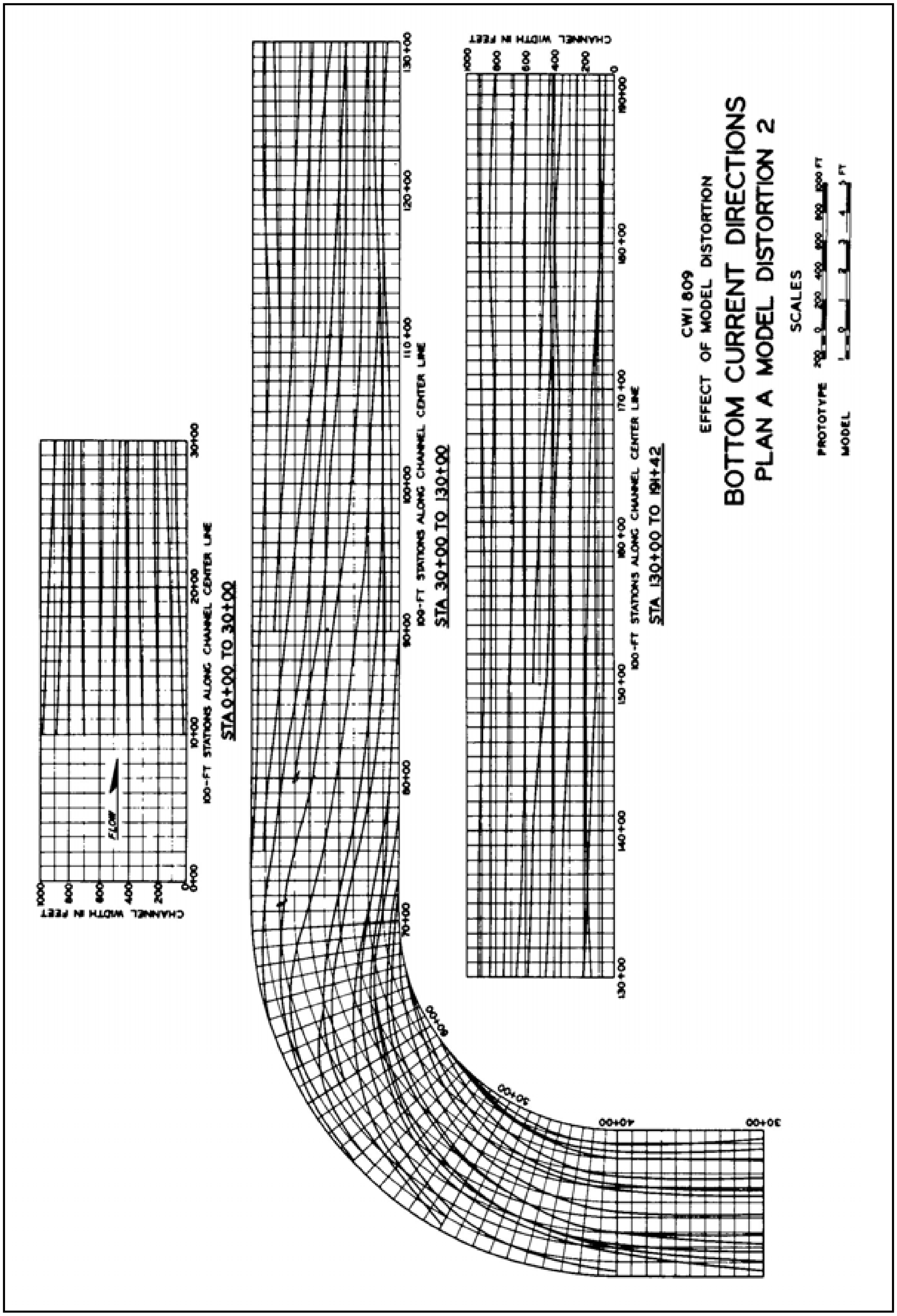
PROTOTYPE 200 0 200 400 600 800 1000 FT

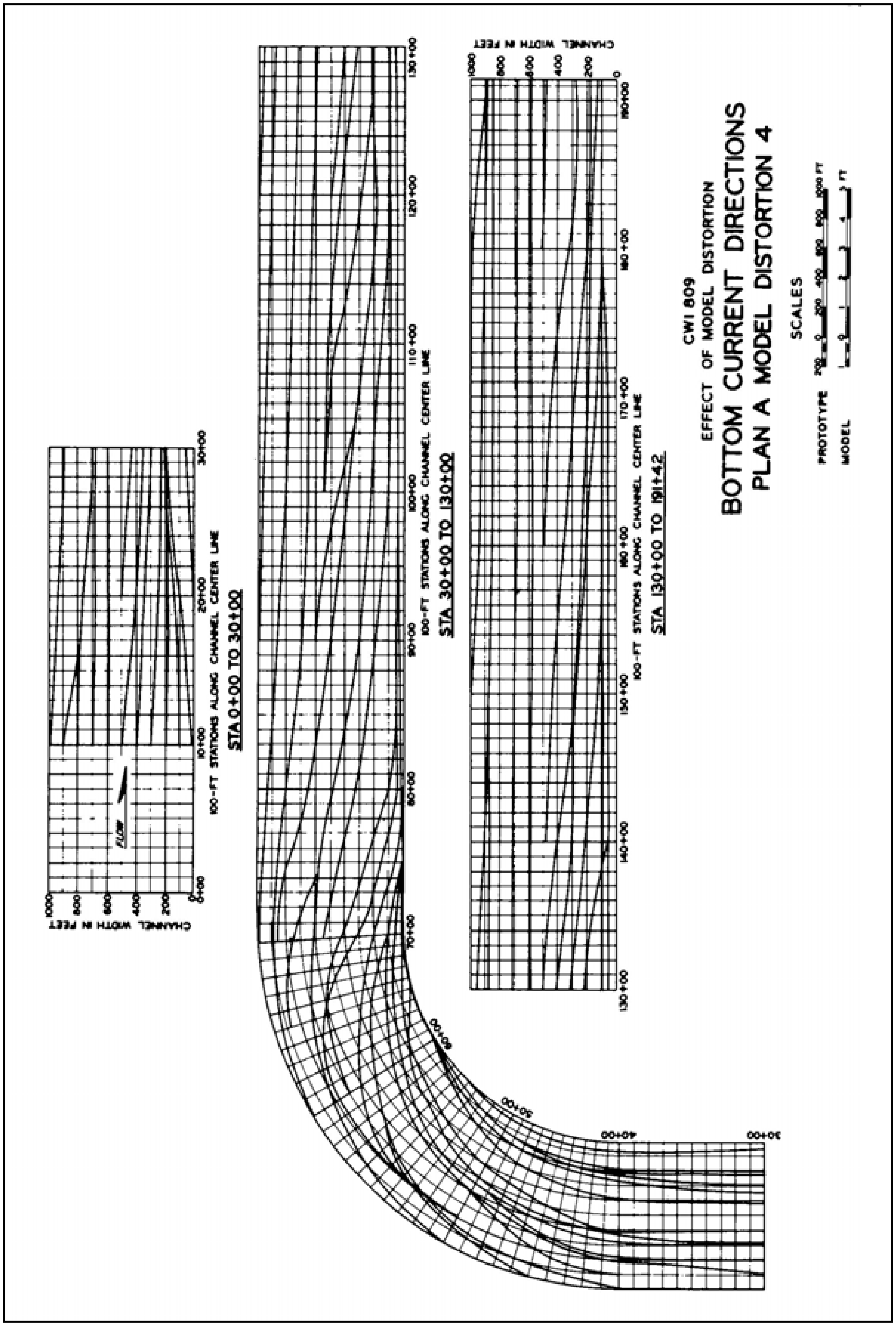
MODEL 1 0 1 2 3 4 5 FT

NOTE: CURRENT DIRECTIONS PLOTTED TO INDICATE TREND FROM STARTING POINT ON RANGE 71+41.6

Plate 8


CWI 809
EFFECT OF MODEL DISTORTION
BOTTOM CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 0
SCALES
PROTOTYPE
MODEL
STA 0+00 TO 30+00
STA 30+00 TO 130+00
STA 130+00 TO 191+42
100-FT STATIONS ALONG CHANNEL CENTER LINE
CHANNEL WIDTH IN FEET
FLOW


CWI 809
EFFECT OF MODEL DISTORTION
BOTTOM CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 2
SCALES
PROTOTYPE
MODEL
FLOW
CHANNEL WIDTH IN FEET
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 0+00 TO 30+00
STA 30+00 TO 130+00
STA 130+00 TO 191+42



CHANNEL WIDTH IN FEET
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 0+00 TO 30+00
FLOW
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 30+00 TO 130+00
CHANNEL WIDTH IN FEET
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 130+00 TO 191+42
CWI 809
EFFECT OF MODEL DISTORTION
BOTTOM CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 4
SCALES
PROTOTYPE
MODEL

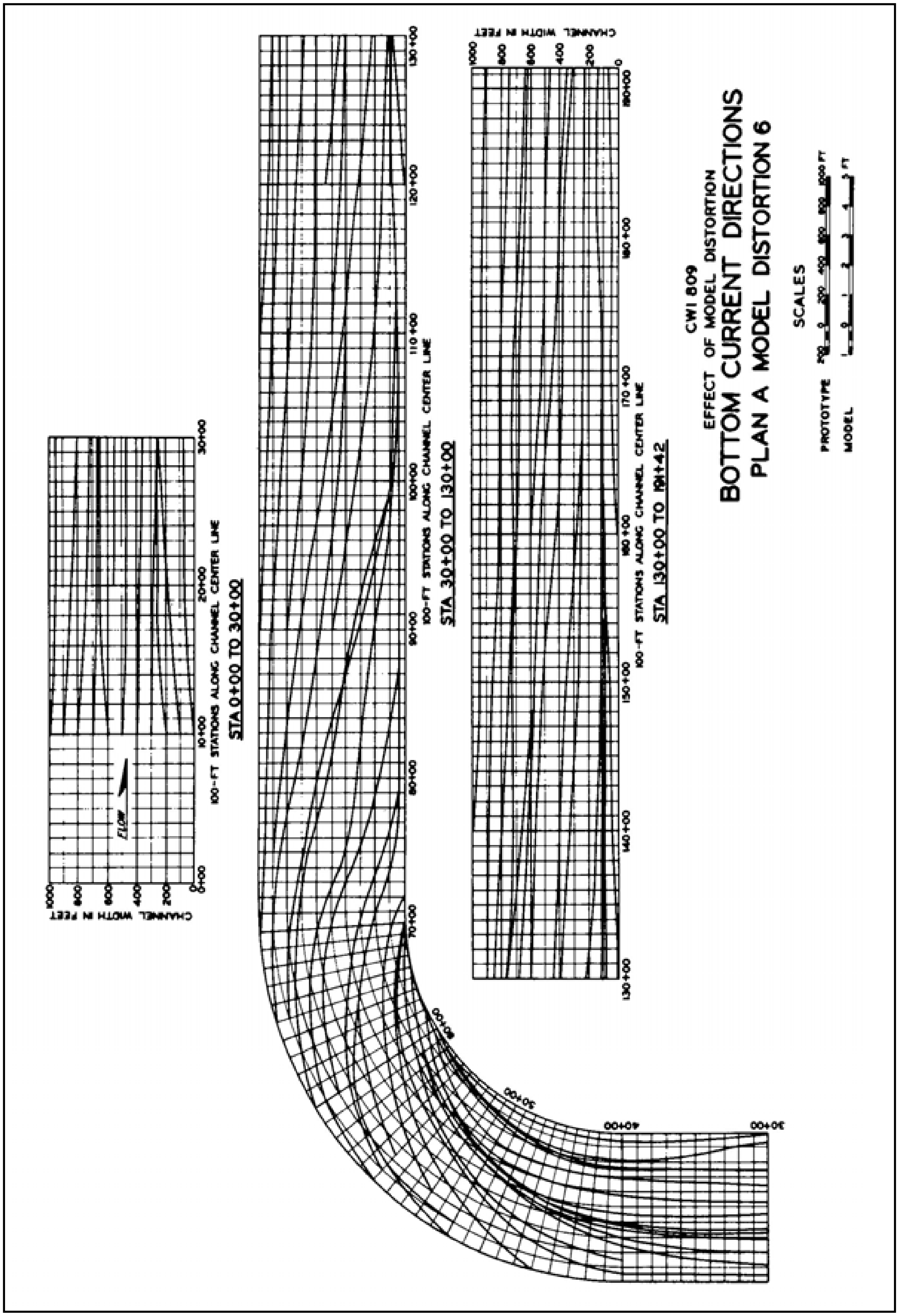
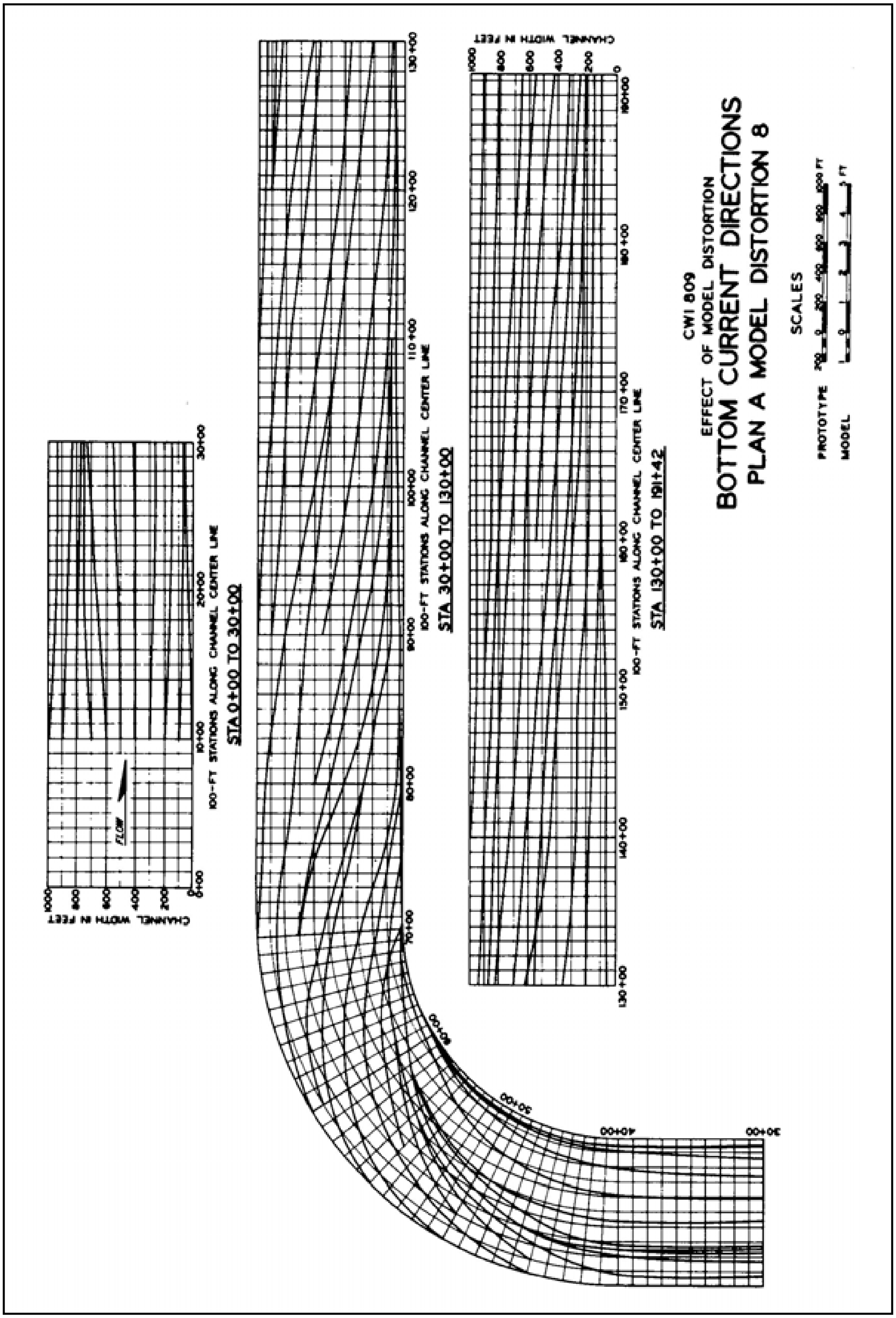

CWI 809
EFFECT OF MODEL DISTORTION
BOTTOM CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 6
SCALES
PROTOTYPE
MODEL
CHANNEL WIDTH IN FEET
FLOW
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 0+00 TO 30+00
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 30+00 TO 130+00
CHANNEL WIDTH IN FEET
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 130+00 TO 191+42

Plate 12


CWI 809
EFFECT OF MODEL DISTORTION
BOTTOM CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 8
SCALES
PROTOTYPE
MODEL
STA 0+00 TO 30+00
STA 30+00 TO 130+00
STA 130+00 TO 191+42
100-FT STATIONS ALONG CHANNEL CENTER LINE
CHANNEL WIDTH IN FEET
FLOW

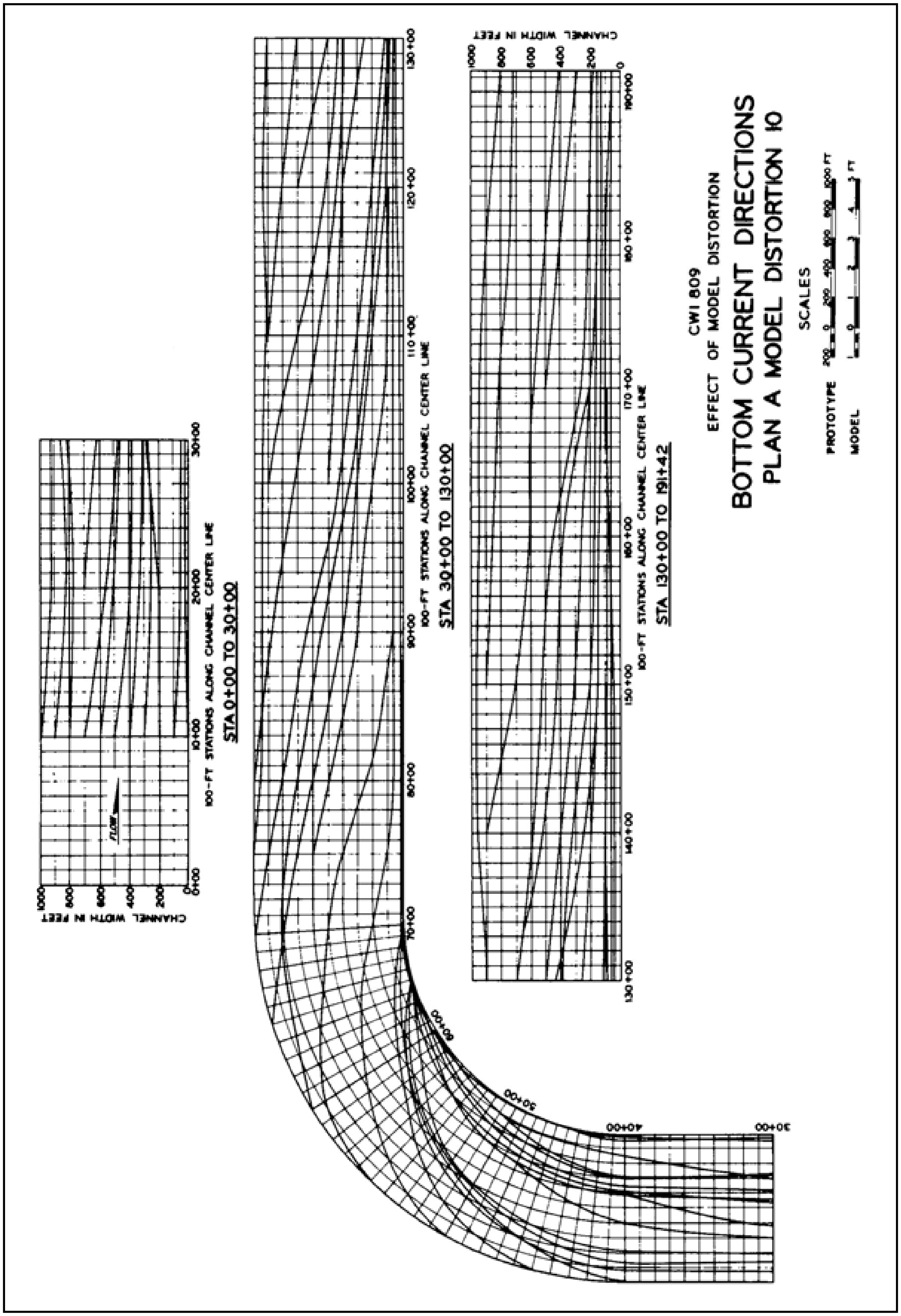
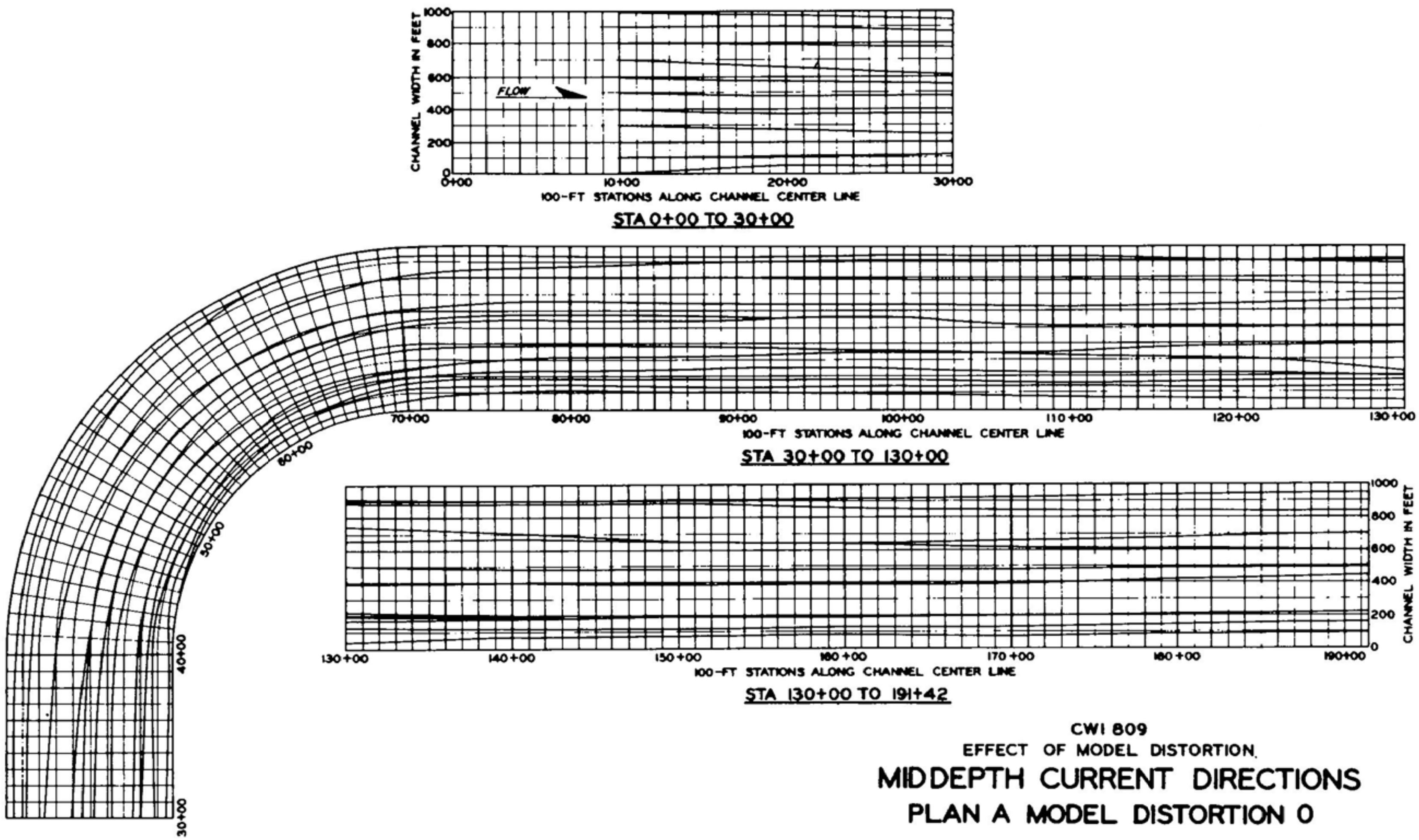

CWI 809
EFFECT OF MODEL DISTORTION
BOTTOM CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 10
SCALES
PROTOTYPE 200 0 200 400 600 800 1000 FT
MODEL 1 0 1 2 3 4 5 FT
STA 0+00 TO 30+00
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 30+00 TO 130+00
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 130+00 TO 191+42
100-FT STATIONS ALONG CHANNEL CENTER LINE
CHANNEL WIDTH IN FEET
FLOW

Plate 14



CWI 809

EFFECT OF MODEL DISTORTION

MIDDEPTH CURRENT DIRECTIONS

PLAN A MODEL DISTORTION 0

SCALES

PROTOTYPE 200 0 200 400 600 800 1000 FT

MODEL 1 0 1 2 3 4 5 FT

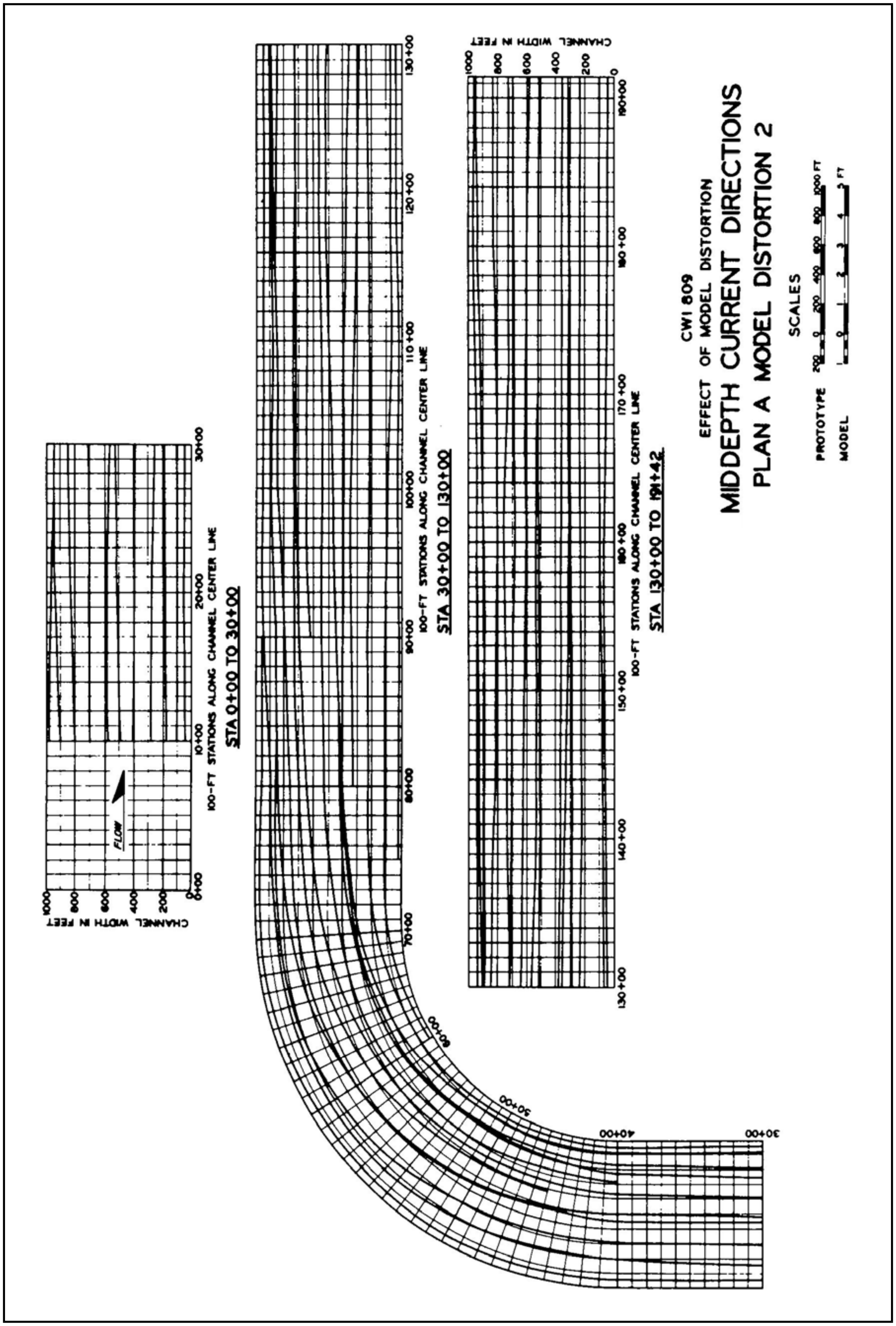
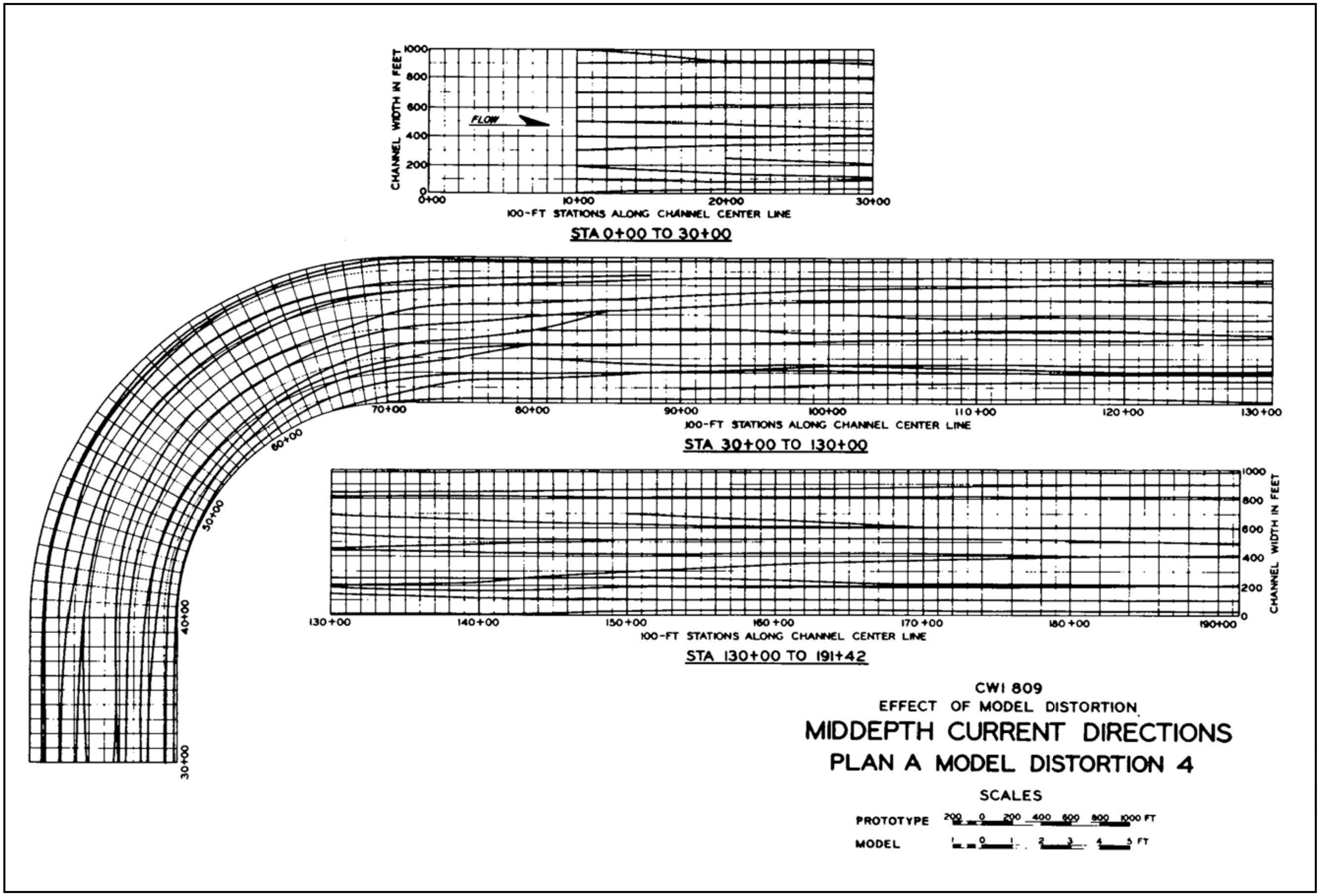
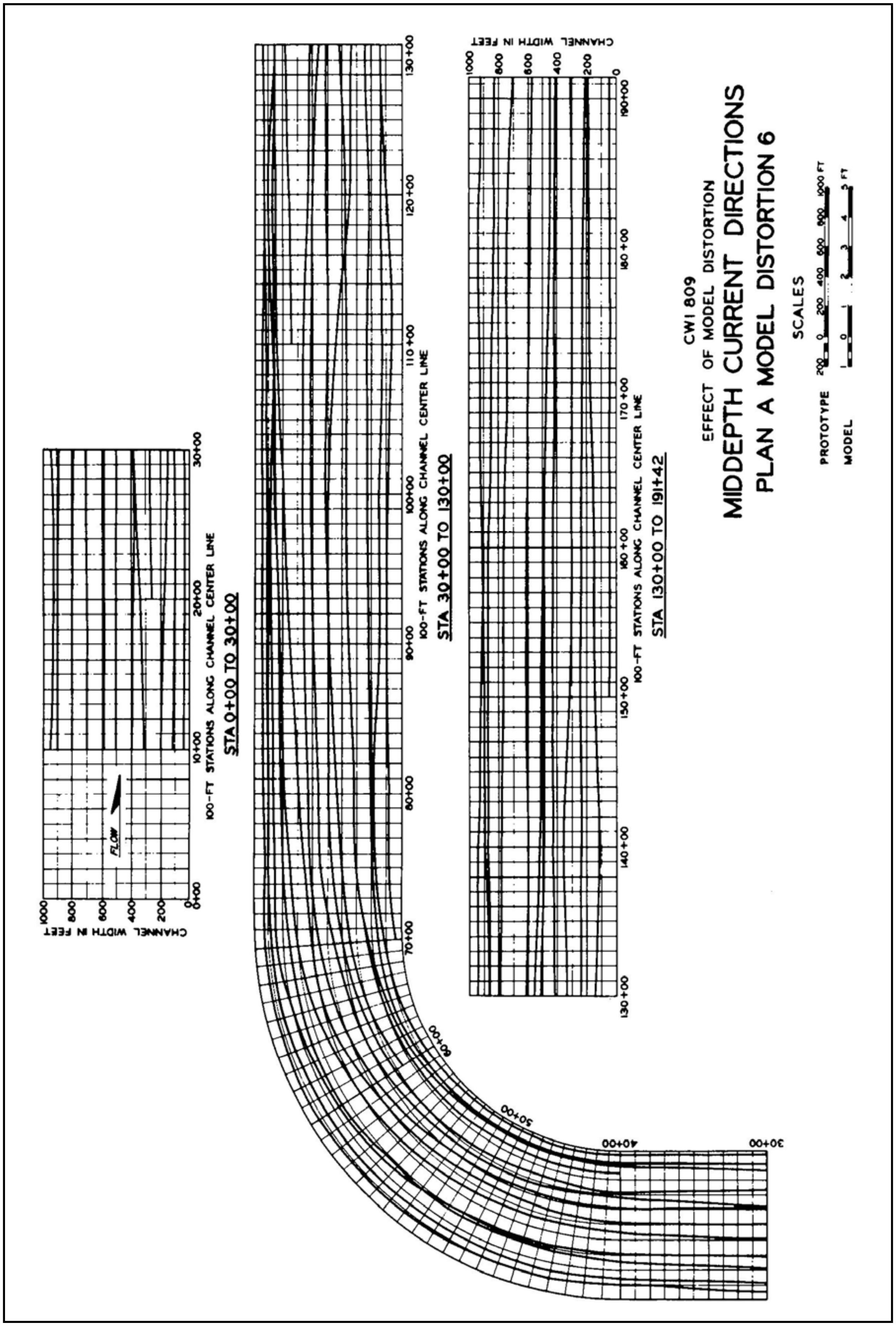
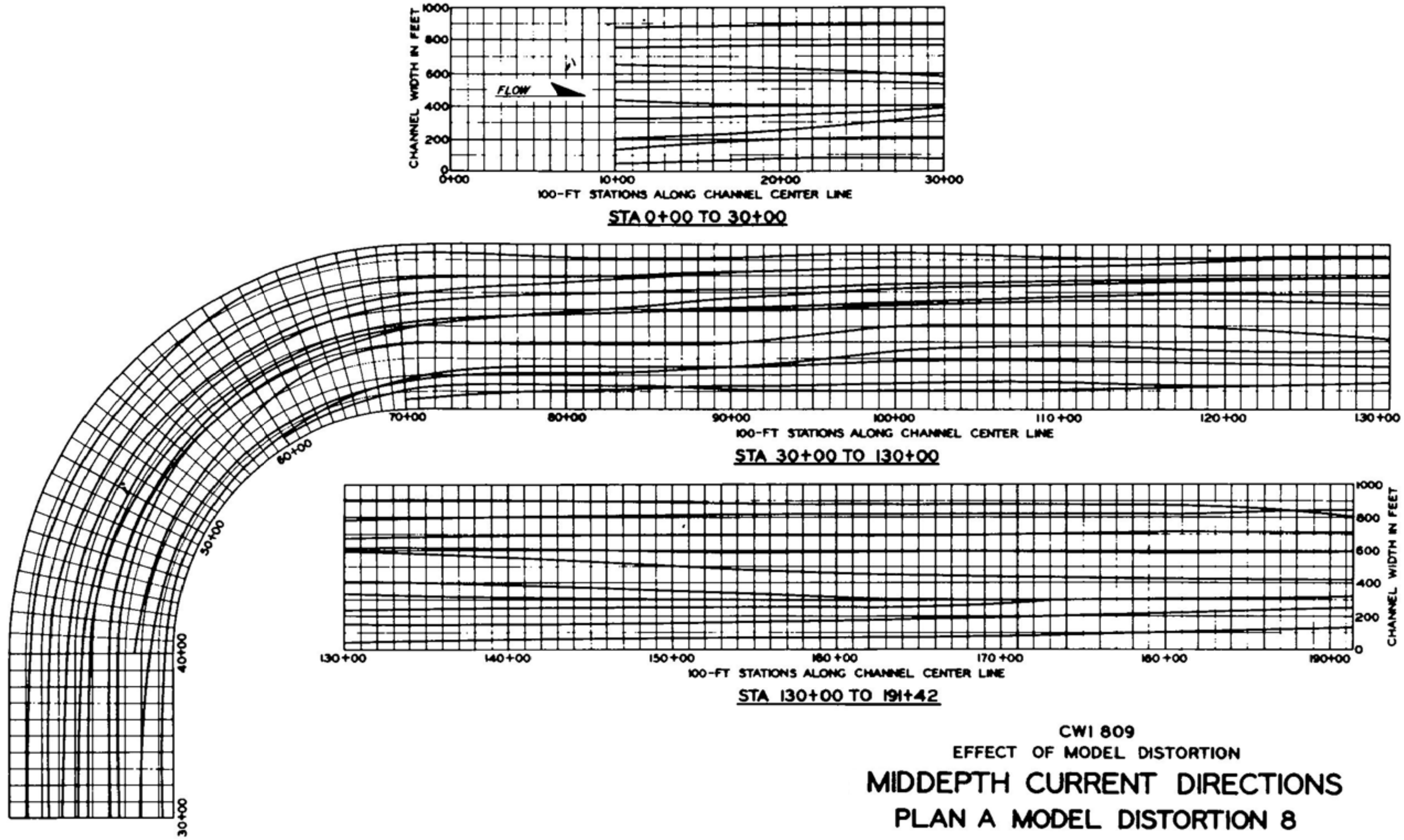

CWI 809
EFFECT OF MODEL DISTORTION
MIDDEPTH CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 2
SCALES
PROTOTYPE
MODEL
FLOW
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 0+00 TO 30+00
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 30+00 TO 130+00
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 130+00 TO 191+42
CHANNEL WIDTH IN FEET
CHANNEL WIDTH IN FEET

Plate 16


CHANNEL WIDTH IN FEET
1000
800
600
400
200
0
FLOW
0+00
10+00
20+00
30+00
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 0+00 TO 30+00
30+00
40+00
50+00
60+00
70+00
80+00
90+00
100+00
110+00
120+00
130+00
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 30+00 TO 130+00
130+00
140+00
150+00
160+00
170+00
180+00
190+00
100-FT STATIONS ALONG CHANNEL CENTER LINE
STA 130+00 TO 191+42
CHANNEL WIDTH IN FEET
CWI 809
EFFECT OF MODEL DISTORTION
MIDDEPTH CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 4
SCALES
PROTOTYPE 200 0 200 400 600 800 1000 FT
MODEL 1 0 1 2 3 4 5 FT



CWI 809
EFFECT OF MODEL DISTORTION
MIDDEPTH CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 6
SCALES
PROTOTYPE
MODEL
STA 0+00 TO 30+00
STA 30+00 TO 130+00
STA 130+00 TO 191+42
100-FT STATIONS ALONG CHANNEL CENTER LINE
CHANNEL WIDTH IN FEET
FLOW



CWI 809

EFFECT OF MODEL DISTORTION

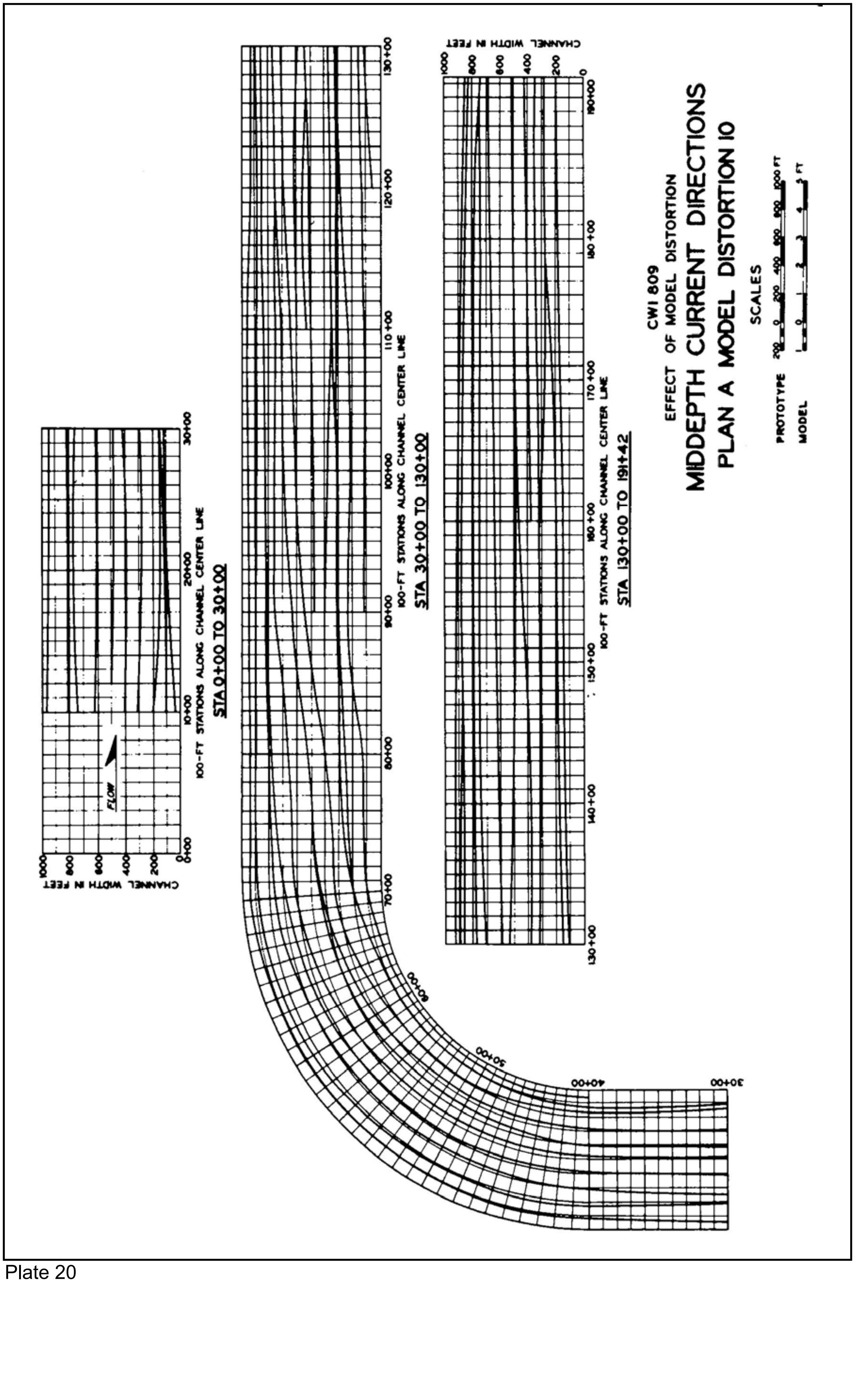
MIDDEPTH CURRENT DIRECTIONS

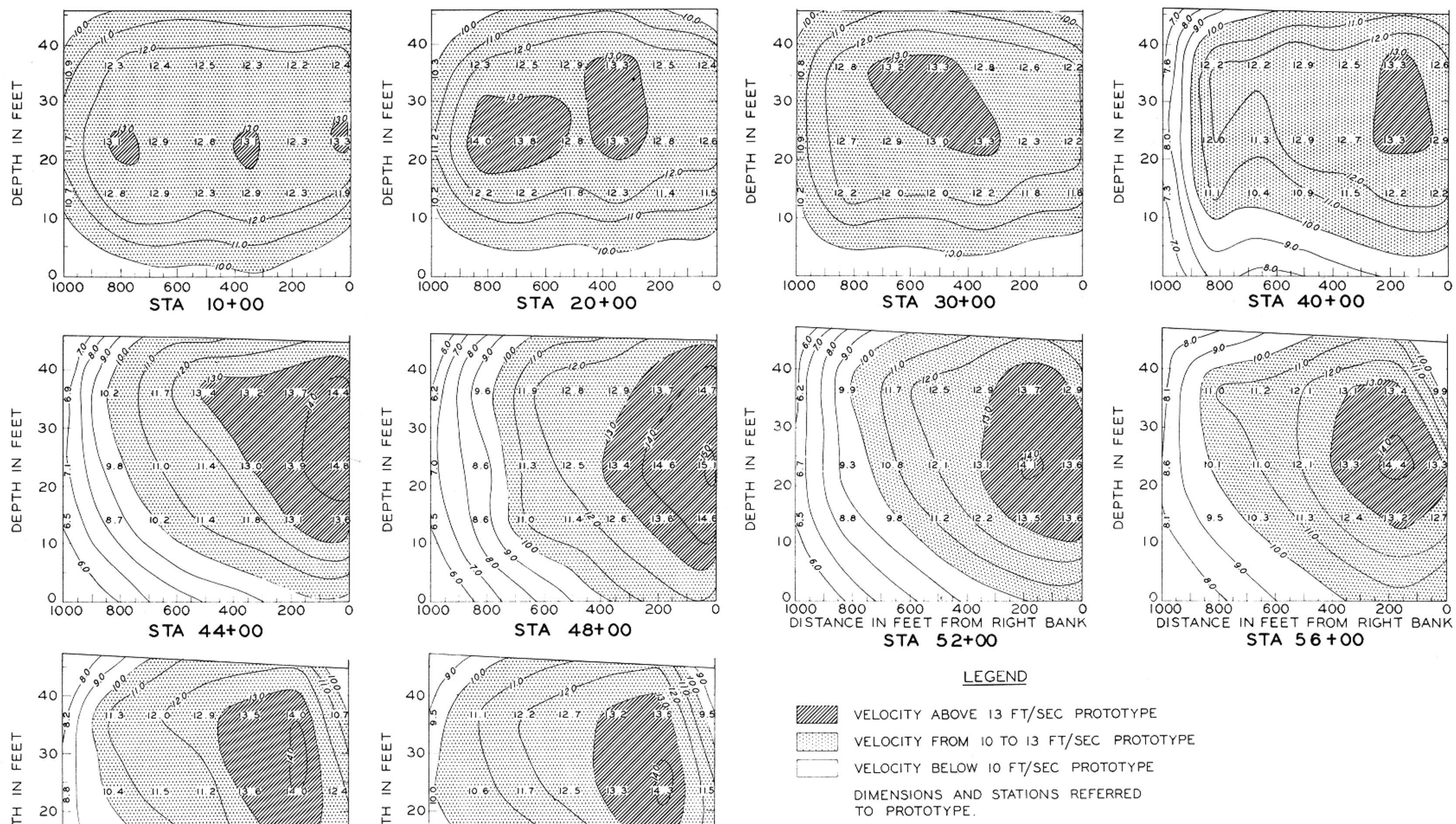
PLAN A MODEL DISTORTION 8

SCALES

PROTOTYPE 200 0 200 400 600 800 1000 FT

MODEL 1 0 1 2 3 4 5 FT

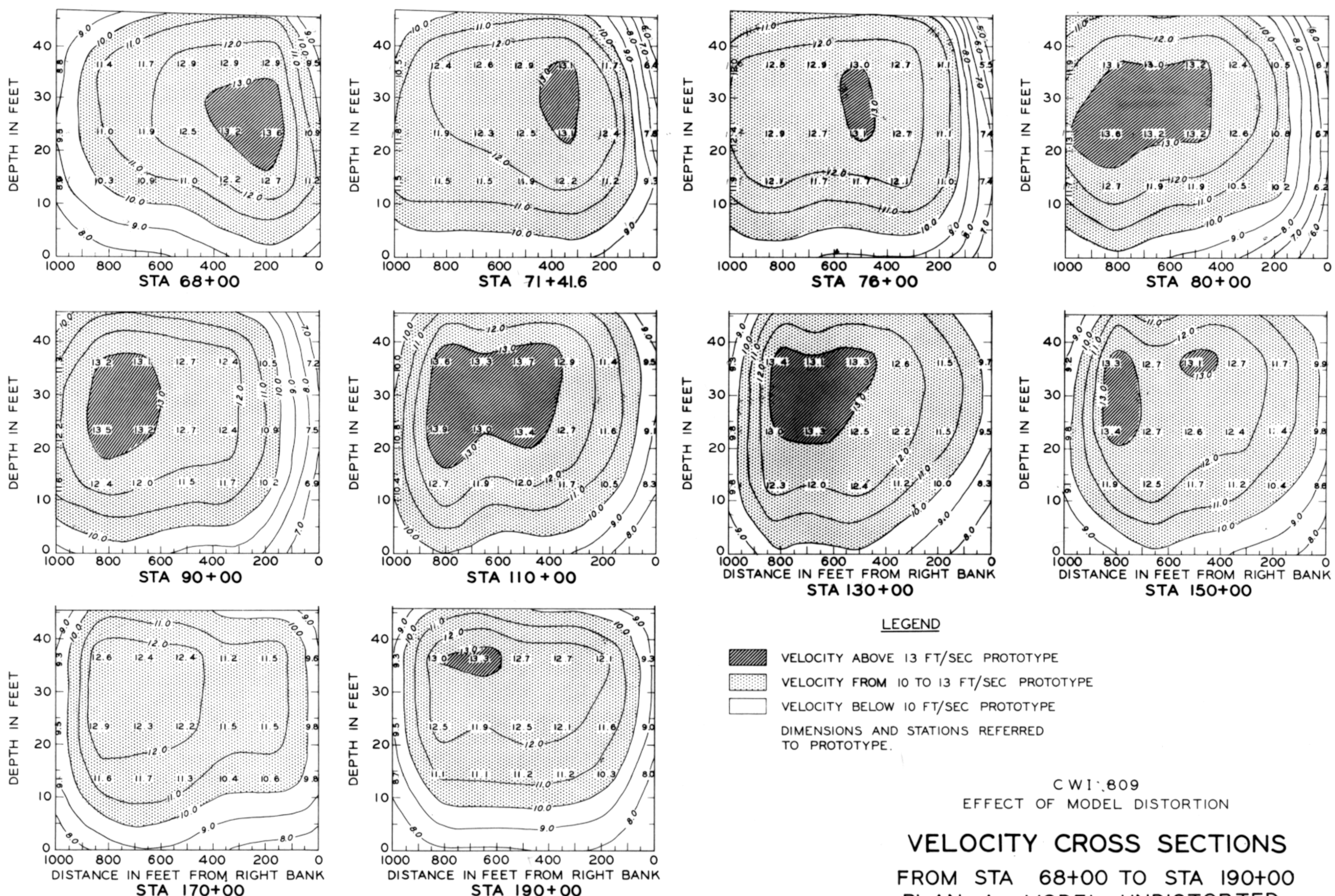

CWI 809
EFFECT OF MODEL DISTORTION
MIDDEPTH CURRENT DIRECTIONS
PLAN A MODEL DISTORTION 10
SCALES
PROTOTYPE
MODEL
STA 0+00 TO 30+00
STA 30+00 TO 130+00
STA 130+00 TO 191+42
100-FT STATIONS ALONG CHANNEL CENTER LINE
CHANNEL WIDTH IN FEET
FLOW



CWI 809
EFFECT OF MODEL DISTORTION

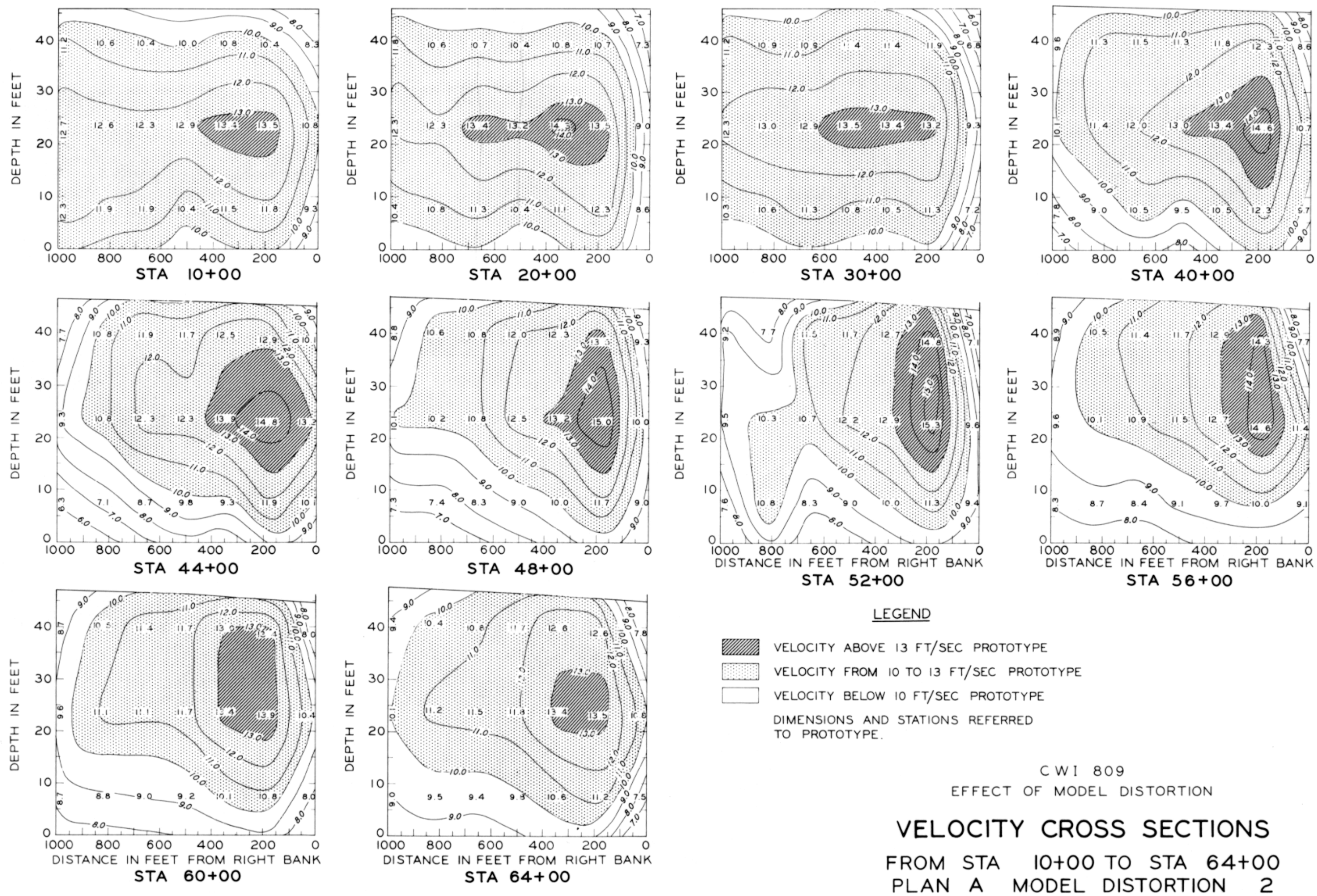
VELOCITY CROSS SECTIONS

FROM STA 10+00 TO STA 64+00
PLAN A MODEL UNDISTORTED



CWI 809
EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS
FROM STA 68+00 TO STA 190+00
PLAN A MODEL UNDISTORTED



CWI 809
EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS

FROM STA 10+00 TO STA 64+00
PLAN A MODEL DISTORTION 2

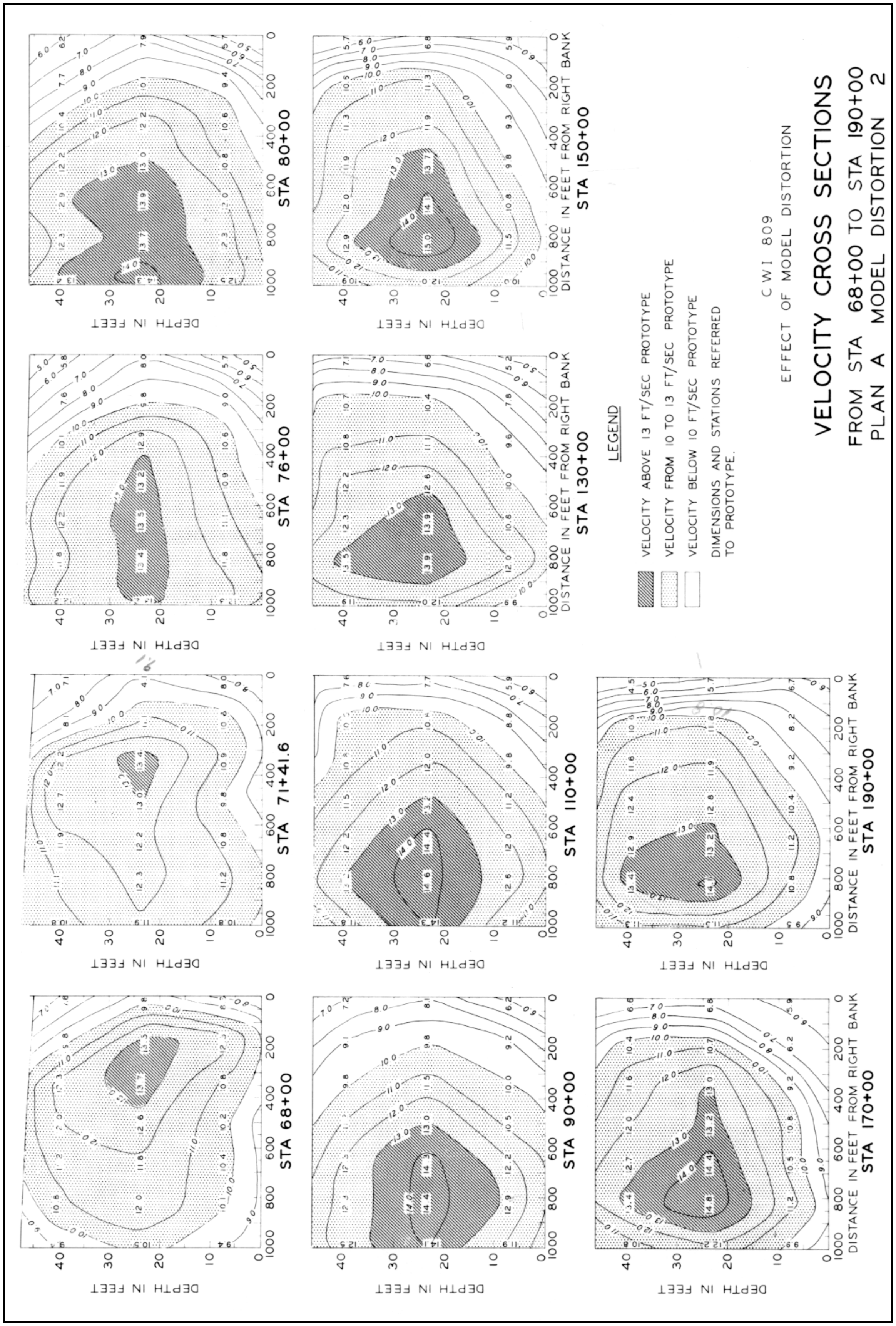
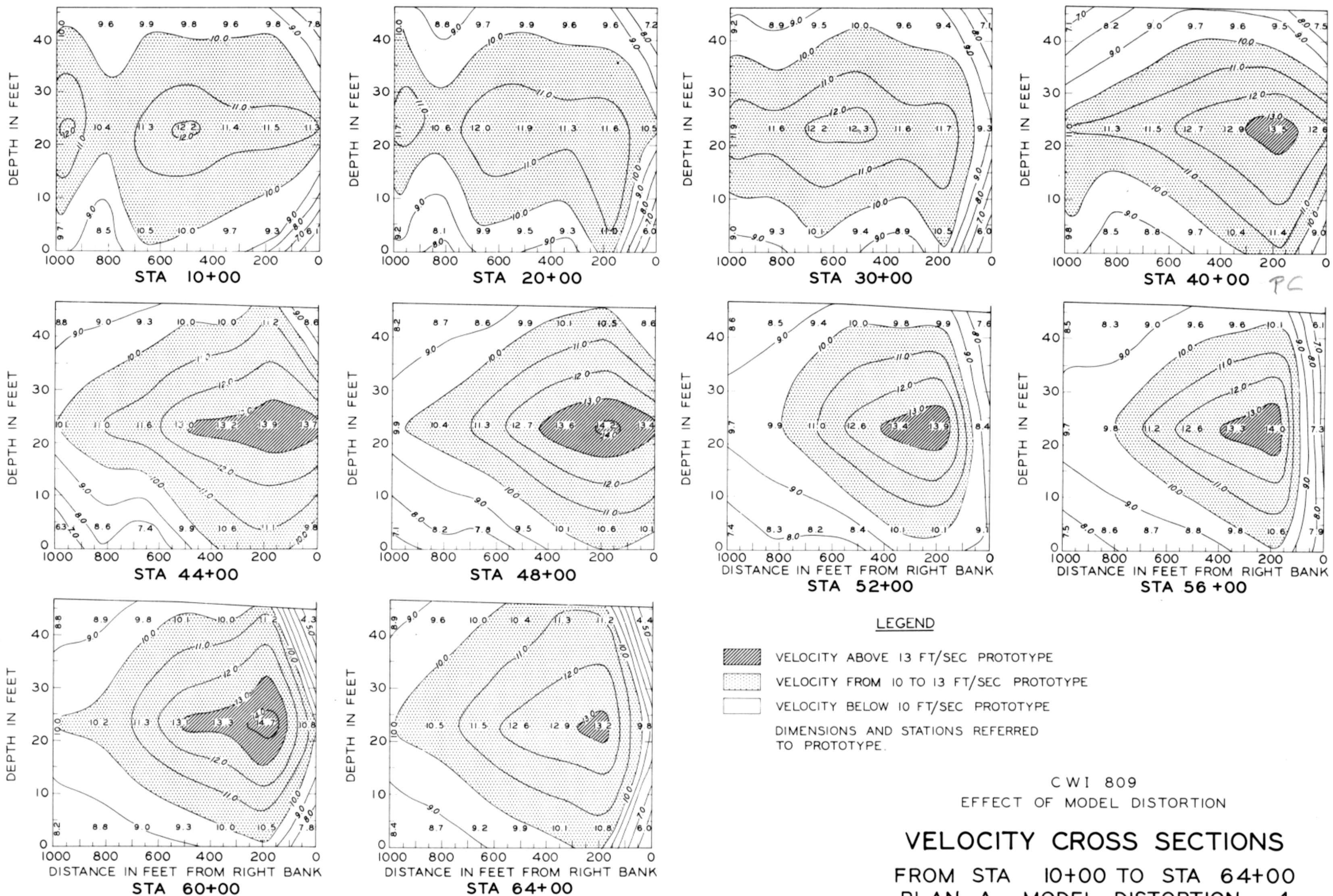

VELOCITY CROSS SECTIONS
FROM STA 68+00 TO STA 190+00
PLAN A MODEL DISTORTION 2
CWI 809
EFFECT OF MODEL DISTORTION
LEGEND
VELOCITY ABOVE 13 FT/SEC PROTOTYPE
VELOCITY FROM 10 TO 13 FT/SEC PROTOTYPE
VELOCITY BELOW 10 FT/SEC PROTOTYPE
DIMENSIONS AND STATIONS REFERRED TO PROTOTYPE.
STA 68+00
STA 71+41.6
STA 76+00
STA 80+00
STA 90+00
STA 110+00
STA 130+00
STA 150+00
STA 170+00
STA 190+00
DEPTH IN FEET
DISTANCE IN FEET FROM RIGHT BANK

Plate 24



LEGEND

VELOCITY ABOVE 13 FT/SEC PROTOTYPE

VELOCITY FROM 10 TO 13 FT/SEC PROTOTYPE

VELOCITY BELOW 10 FT/SEC PROTOTYPE

DIMENSIONS AND STATIONS REFERRED TO PROTOTYPE.

CWI 809
EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS

FROM STA 10+00 TO STA 64+00
PLAN A MODEL DISTORTION 4

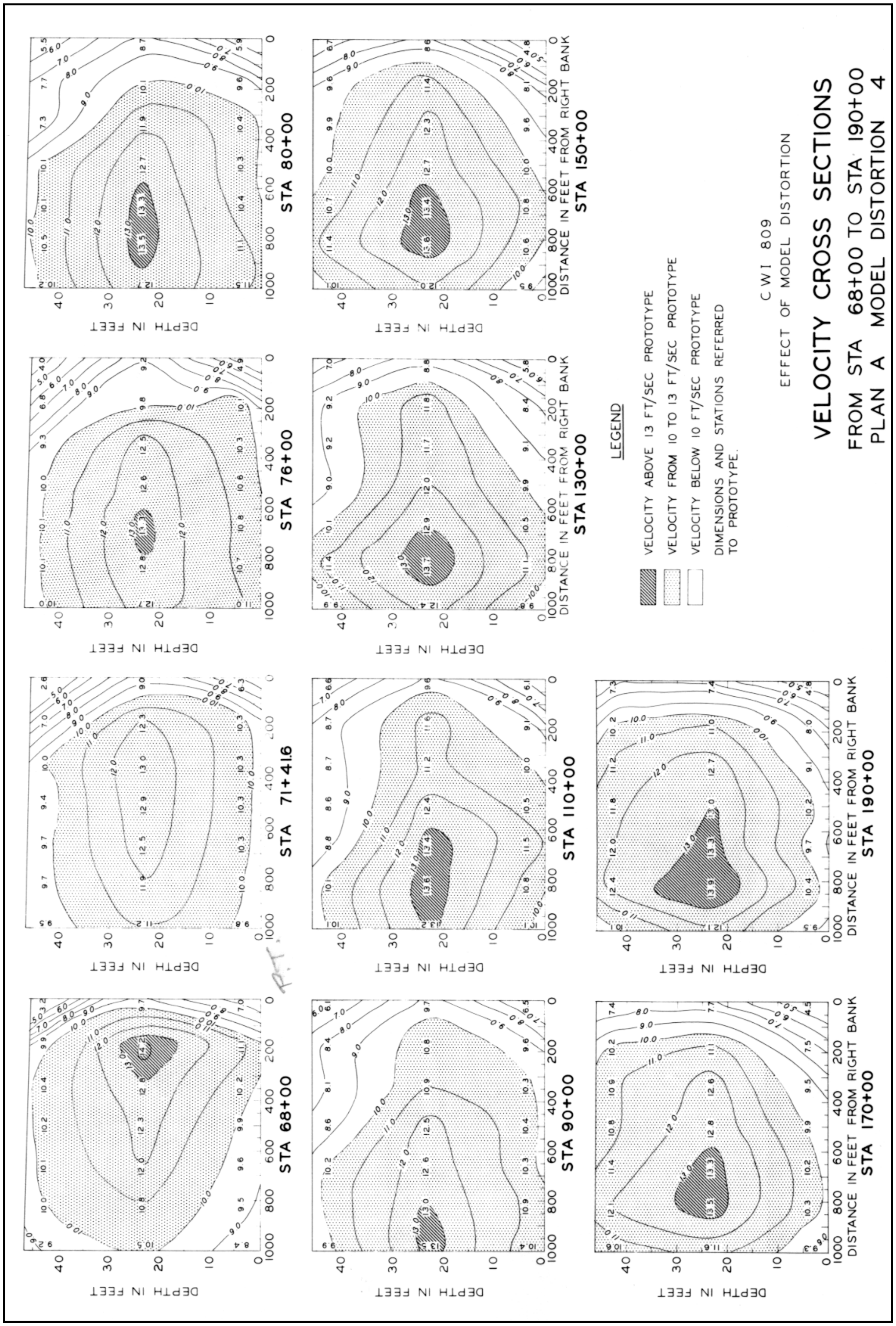
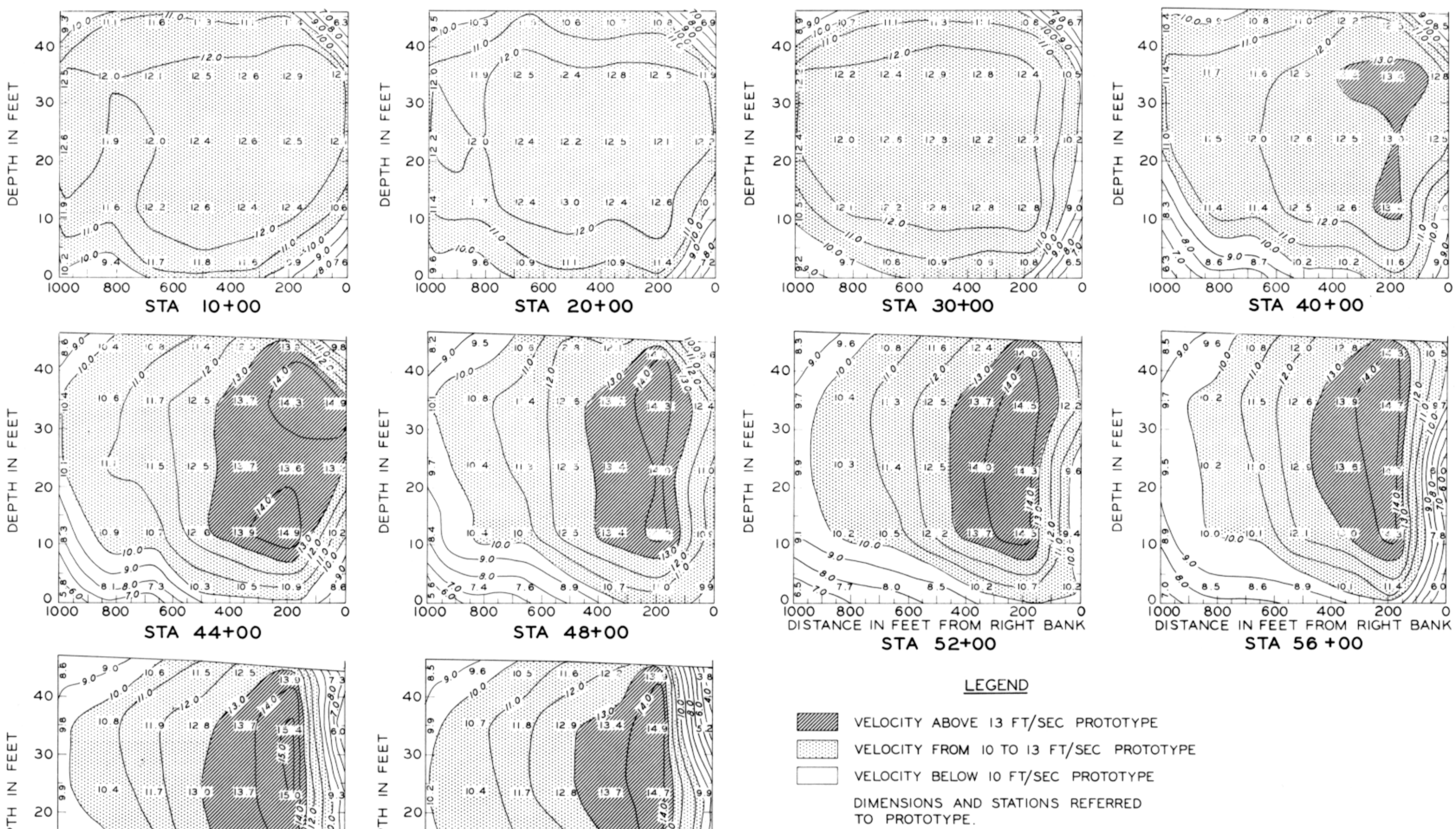

STA 68+00
STA 71+41.6
STA 76+00
STA 80+00
STA 90+00
STA 110+00
STA 130+00
STA 150+00
STA 170+00
STA 190+00
DEPTH IN FEET
DISTANCE IN FEET FROM RIGHT BANK
LEGEND
VELOCITY ABOVE 13 FT/SEC PROTOTYPE
VELOCITY FROM 10 TO 13 FT/SEC PROTOTYPE
VELOCITY BELOW 10 FT/SEC PROTOTYPE
DIMENSIONS AND STATIONS REFERRED TO PROTOTYPE.
CWI 809
EFFECT OF MODEL DISTORTION
VELOCITY CROSS SECTIONS
FROM STA 68+00 TO STA 190+00
PLAN A MODEL DISTORTION 4

Plate 26



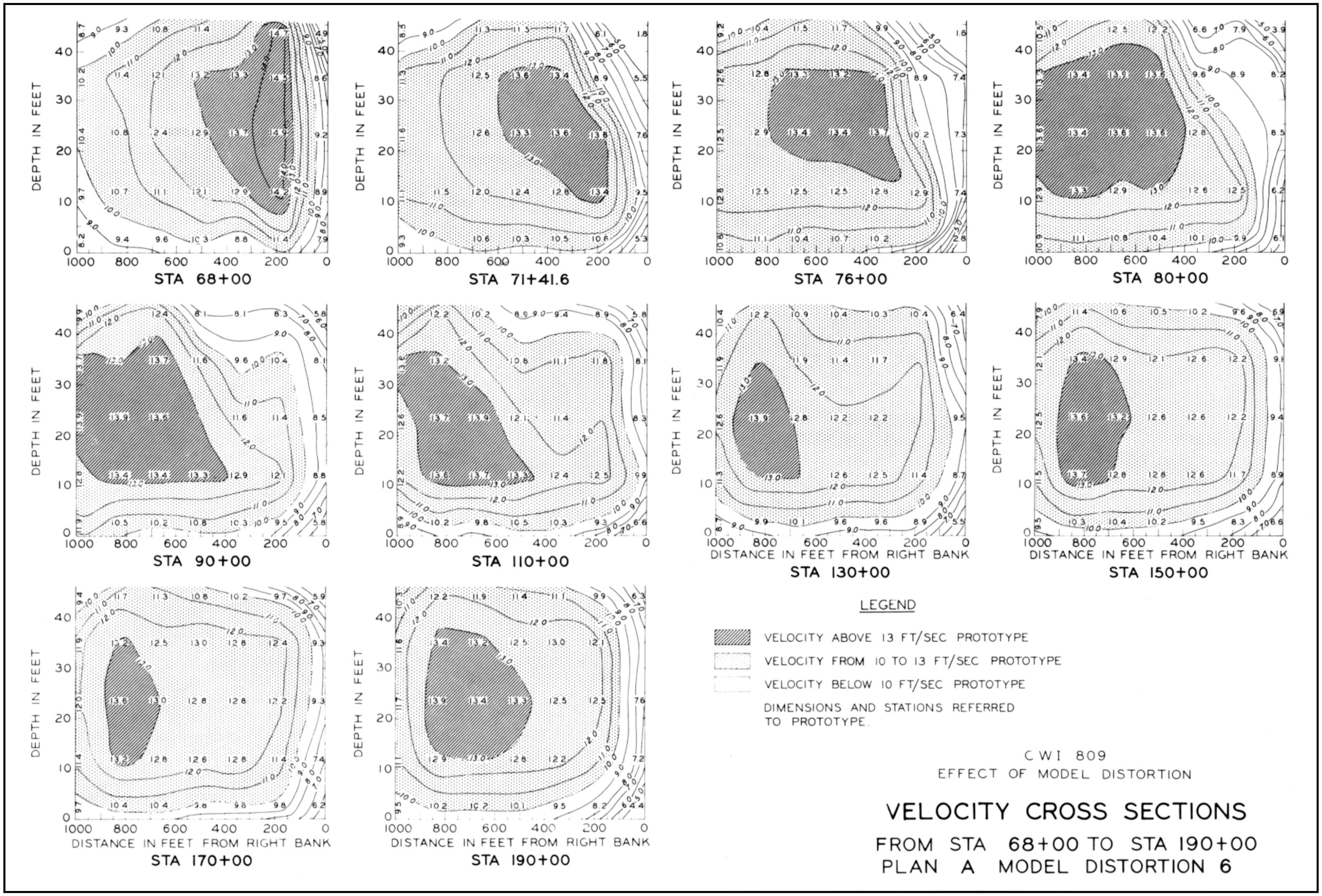
CWI 809

EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS

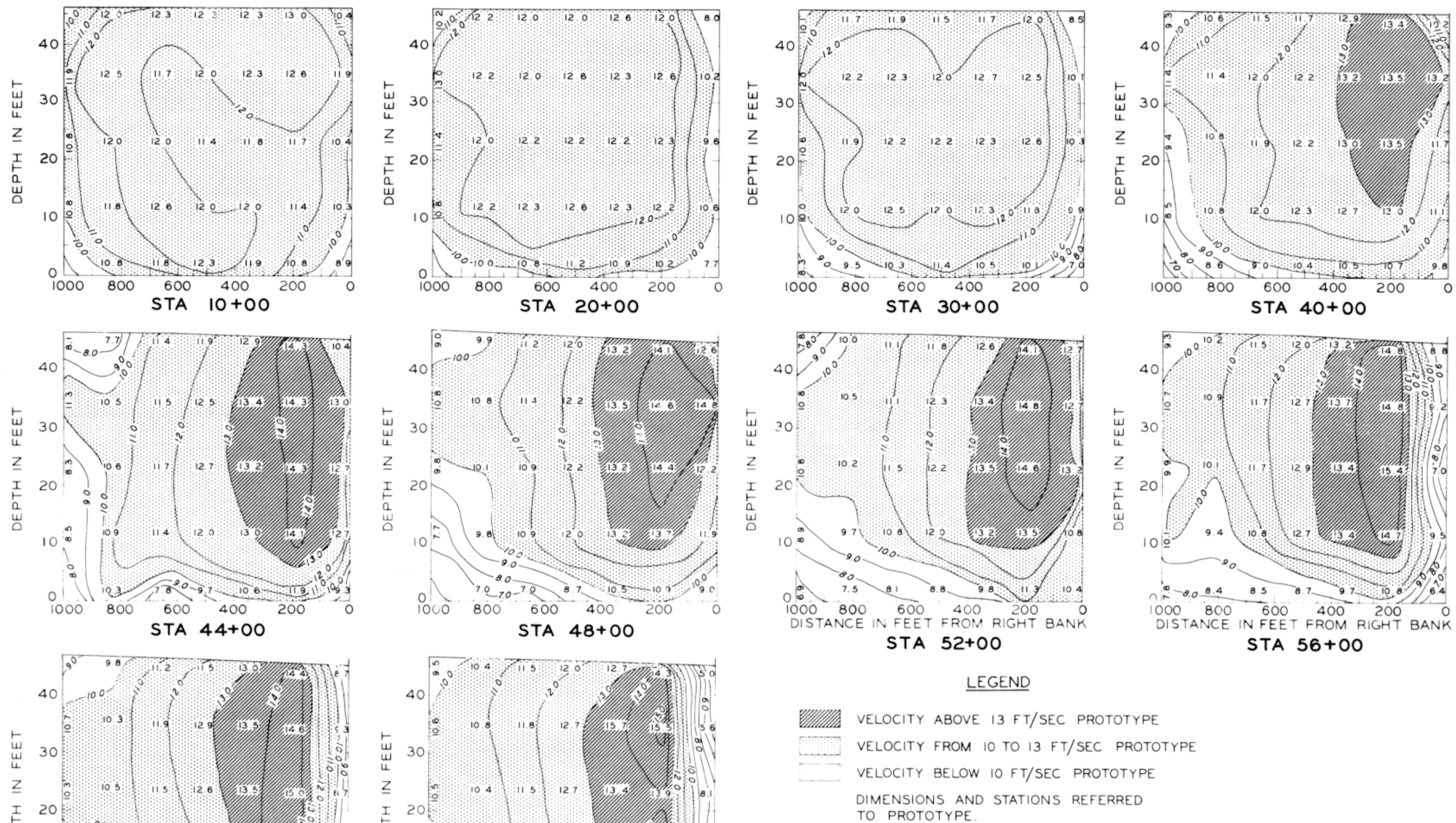
FROM STA 10+00 TO STA 64+00

PLAN A MODEL DISTORTION 6



STA 68+00
STA 71+41.6
STA 76+00
STA 80+00
STA 90+00
STA 110+00
STA 130+00
STA 150+00
STA 170+00
STA 190+00
DEPTH IN FEET
DISTANCE IN FEET FROM RIGHT BANK
LEGEND
VELOCITY ABOVE 13 FT/SEC PROTOTYPE
VELOCITY FROM 10 TO 13 FT/SEC PROTOTYPE
VELOCITY BELOW 10 FT/SEC PROTOTYPE
DIMENSIONS AND STATIONS REFERRED TO PROTOTYPE.
CWI 809
EFFECT OF MODEL DISTORTION
VELOCITY CROSS SECTIONS
FROM STA 68+00 TO STA 190+00
PLAN A MODEL DISTORTION 6

Plate 28

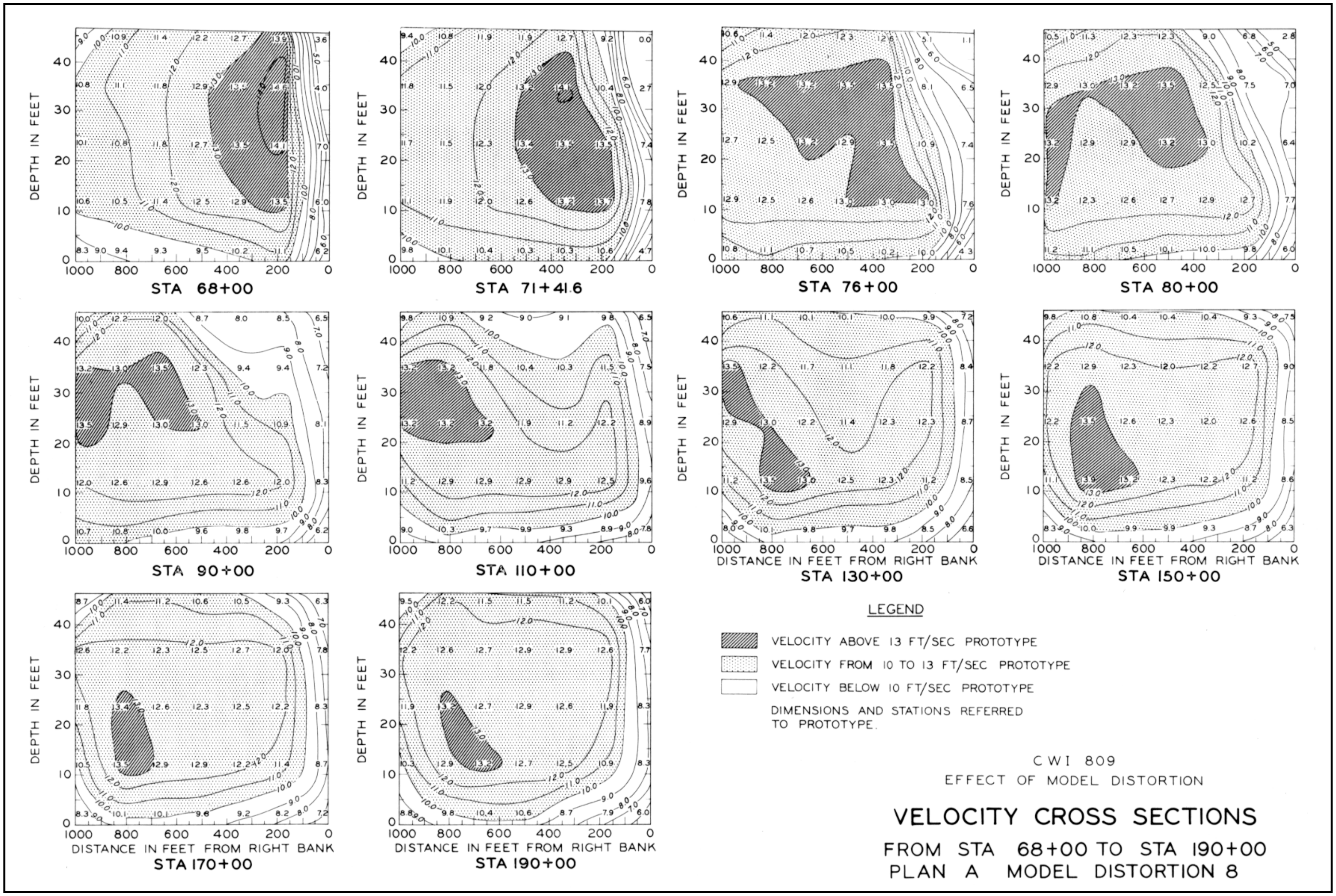


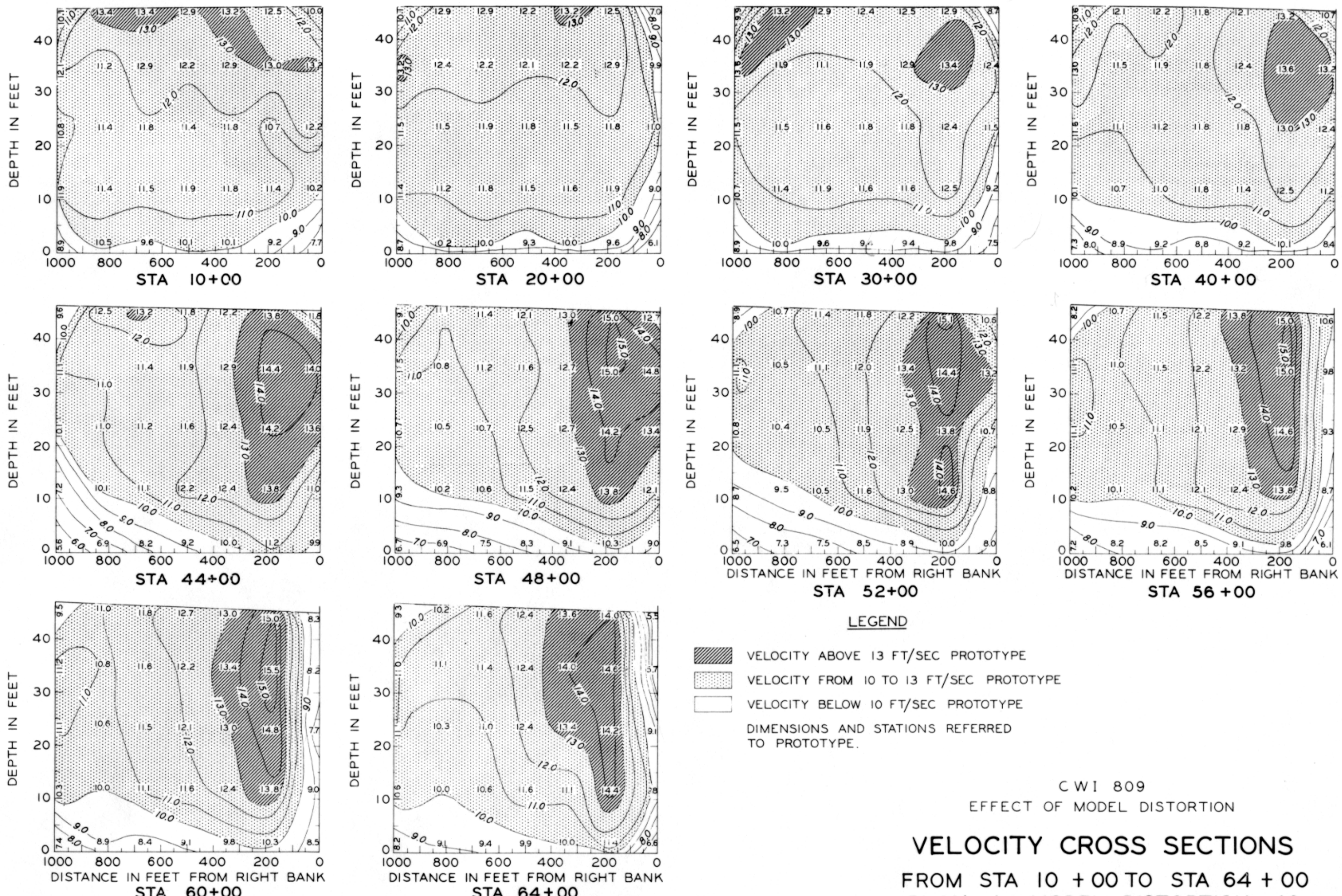
CWI 809
EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS

FROM STA 10+00 TO STA 64+00
PLAN A MODEL DISTORTION 8

Plate 30


STA 68+00
STA 71+41.6
STA 76+00
STA 80+00
STA 90+00
STA 110+00
STA 130+00
STA 150+00
STA 170+00
STA 190+00
DEPTH IN FEET
DISTANCE IN FEET FROM RIGHT BANK
LEGEND
VELOCITY ABOVE 13 FT/SEC PROTOTYPE
VELOCITY FROM 10 TO 13 FT/SEC PROTOTYPE
VELOCITY BELOW 10 FT/SEC PROTOTYPE
DIMENSIONS AND STATIONS REFERRED TO PROTOTYPE.
CWI 809
EFFECT OF MODEL DISTORTION
VELOCITY CROSS SECTIONS
FROM STA 68+00 TO STA 190+00
PLAN A MODEL DISTORTION 8



LEGEND

VELOCITY ABOVE 13 FT/SEC PROTOTYPE

VELOCITY FROM 10 TO 13 FT/SEC PROTOTYPE

VELOCITY BELOW 10 FT/SEC PROTOTYPE

DIMENSIONS AND STATIONS REFERRED TO PROTOTYPE.

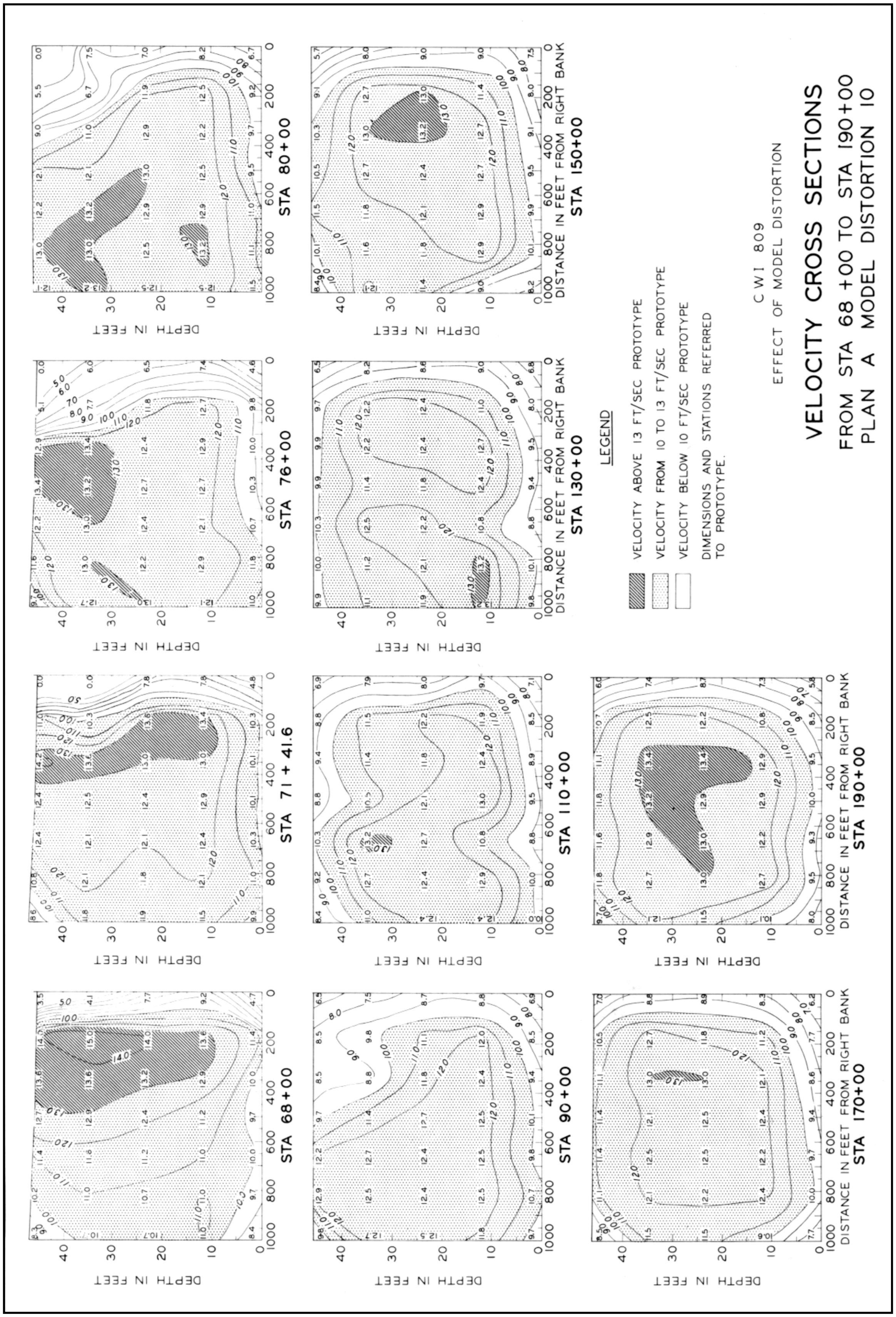
CWI 809

EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS

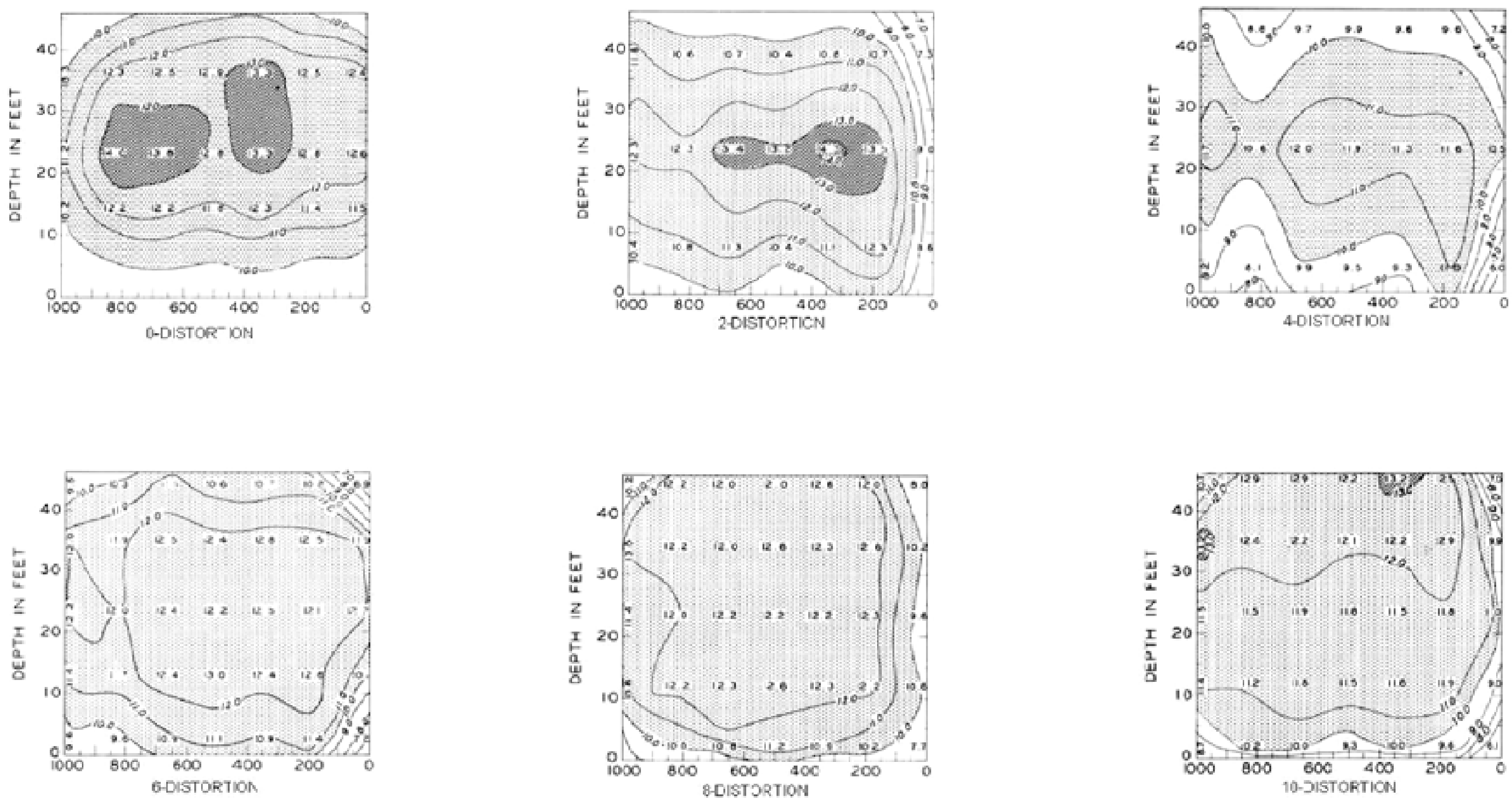
FROM STA 10 + 00 TO STA 64 + 00

PLAN A MODEL DISTORTION 10



STA 68+00
STA 71 + 41.6
STA 76+00
STA 80+00
STA 90+00
STA 110+00
STA 130+00
STA 150+00
STA 170+00
STA 190+00
DEPTH IN FEET
DISTANCE IN FEET FROM RIGHT BANK
LEGEND
VELOCITY ABOVE 13 FT/SEC PROTOTYPE
VELOCITY FROM 10 TO 13 FT/SEC PROTOTYPE
VELOCITY BELOW 10 FT/SEC PROTOTYPE
DIMENSIONS AND STATIONS REFERRED TO PROTOTYPE.
CWI 809
EFFECT OF MODEL DISTORTION
VELOCITY CROSS SECTIONS
FROM STA 68 +00 TO STA 190+00
PLAN A MODEL DISTORTION 10

Plate 32

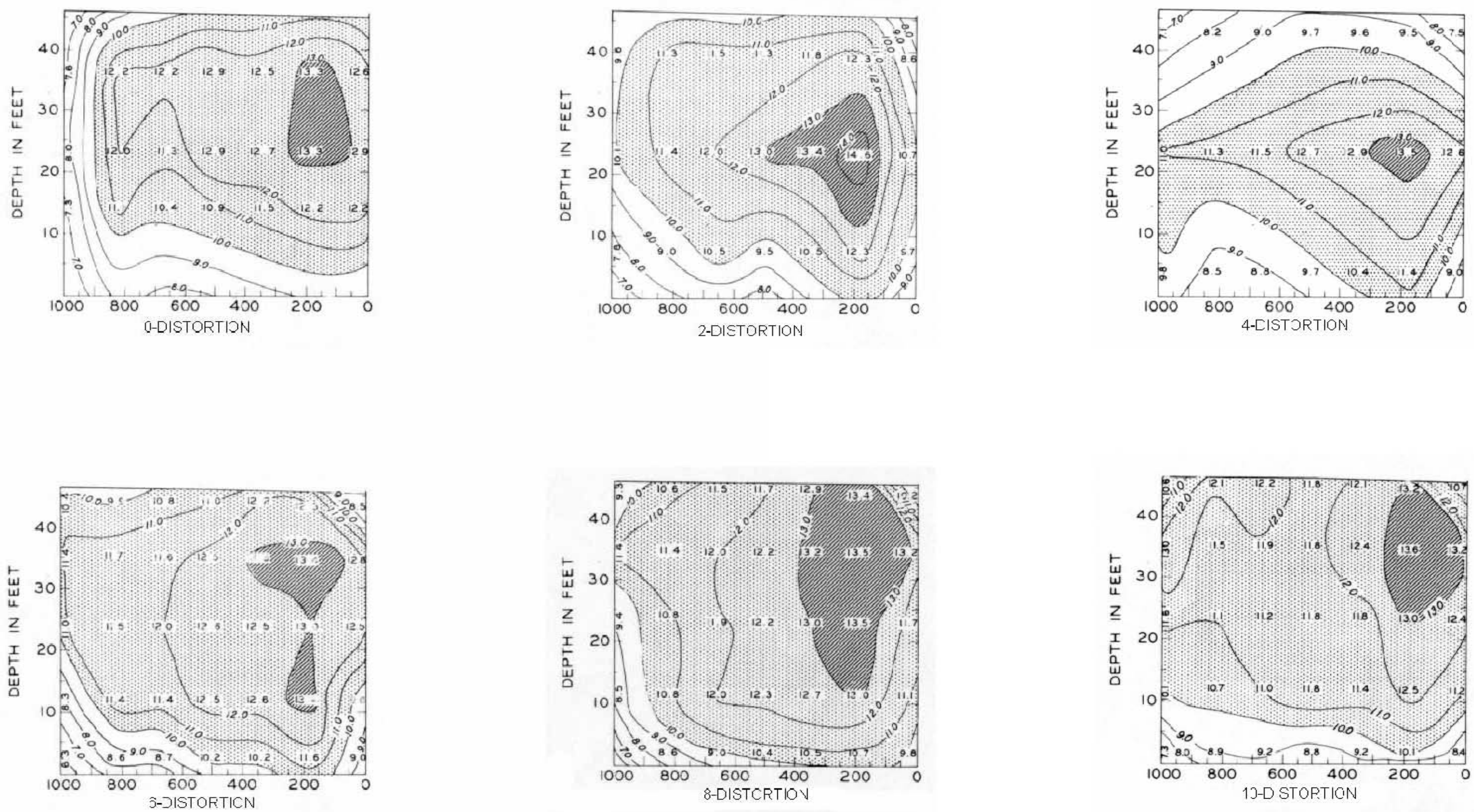


EFFECT OF MODEL DISTORTION

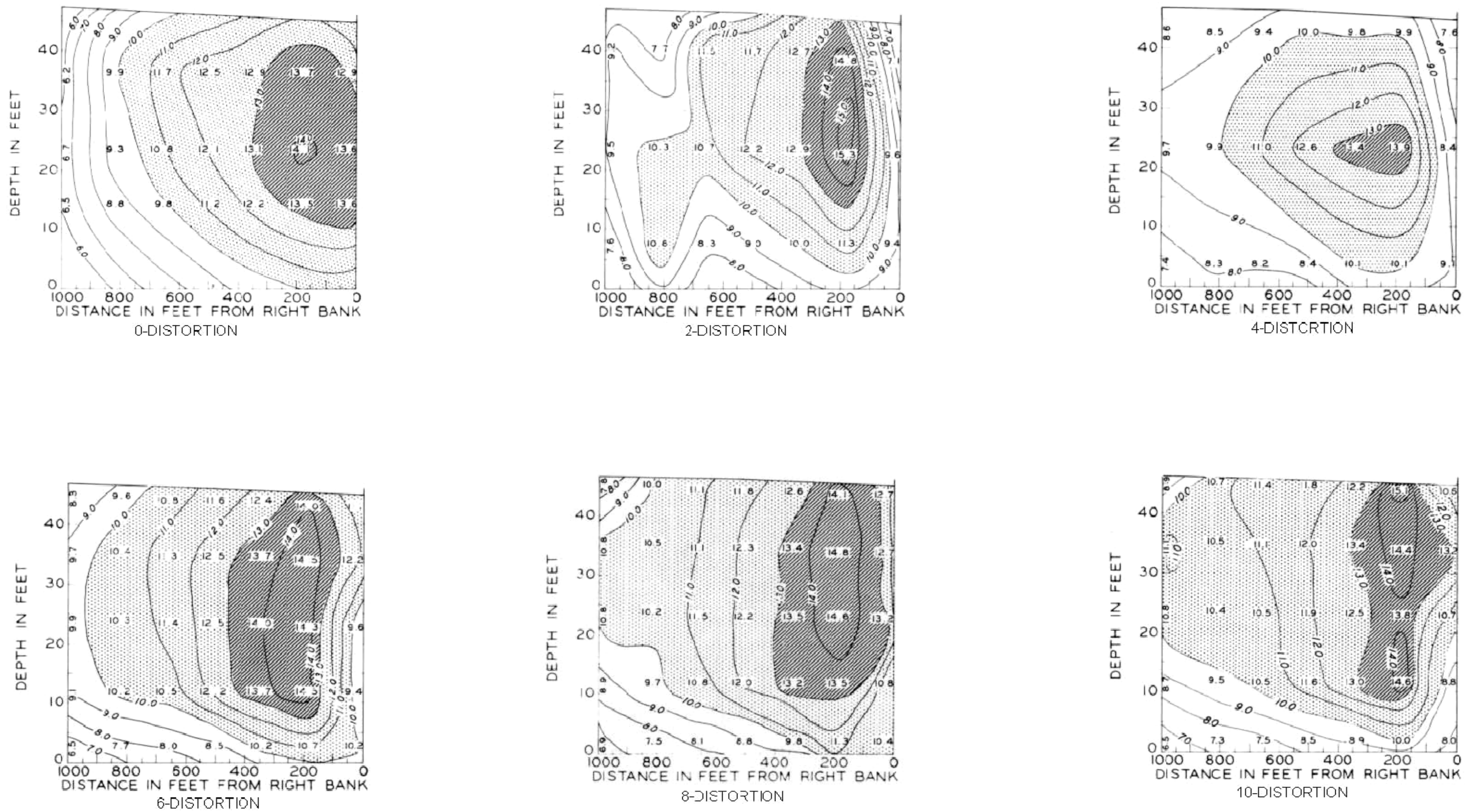
VELOCITY CROSS SECTIONS

PLAN A

STATION 20+00



EFFECT OF MODEL DISTORTION
VELOCITY CROSS SECTIONS
PLAN A
STATION 40+00

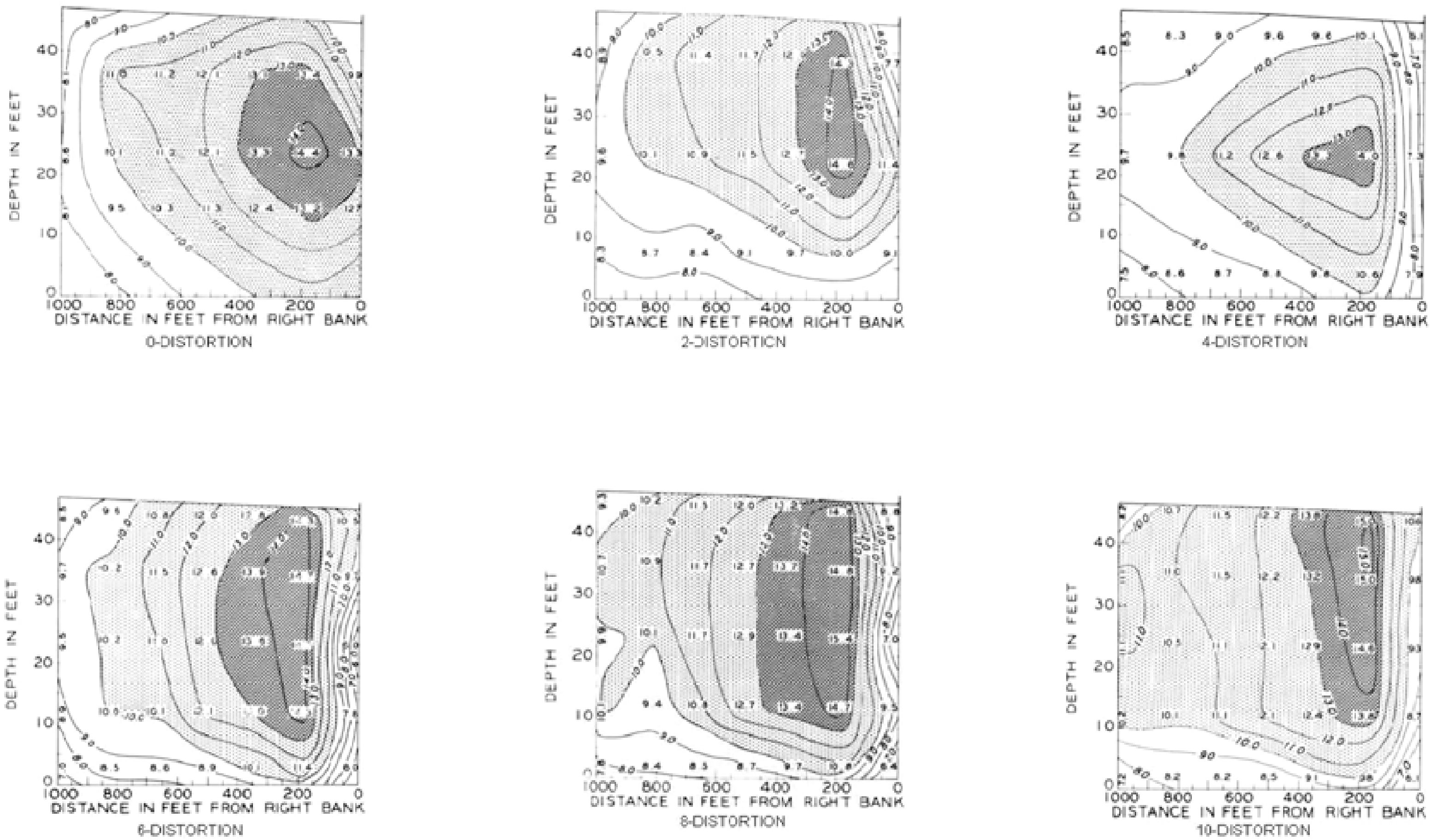


EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS

PLAN A

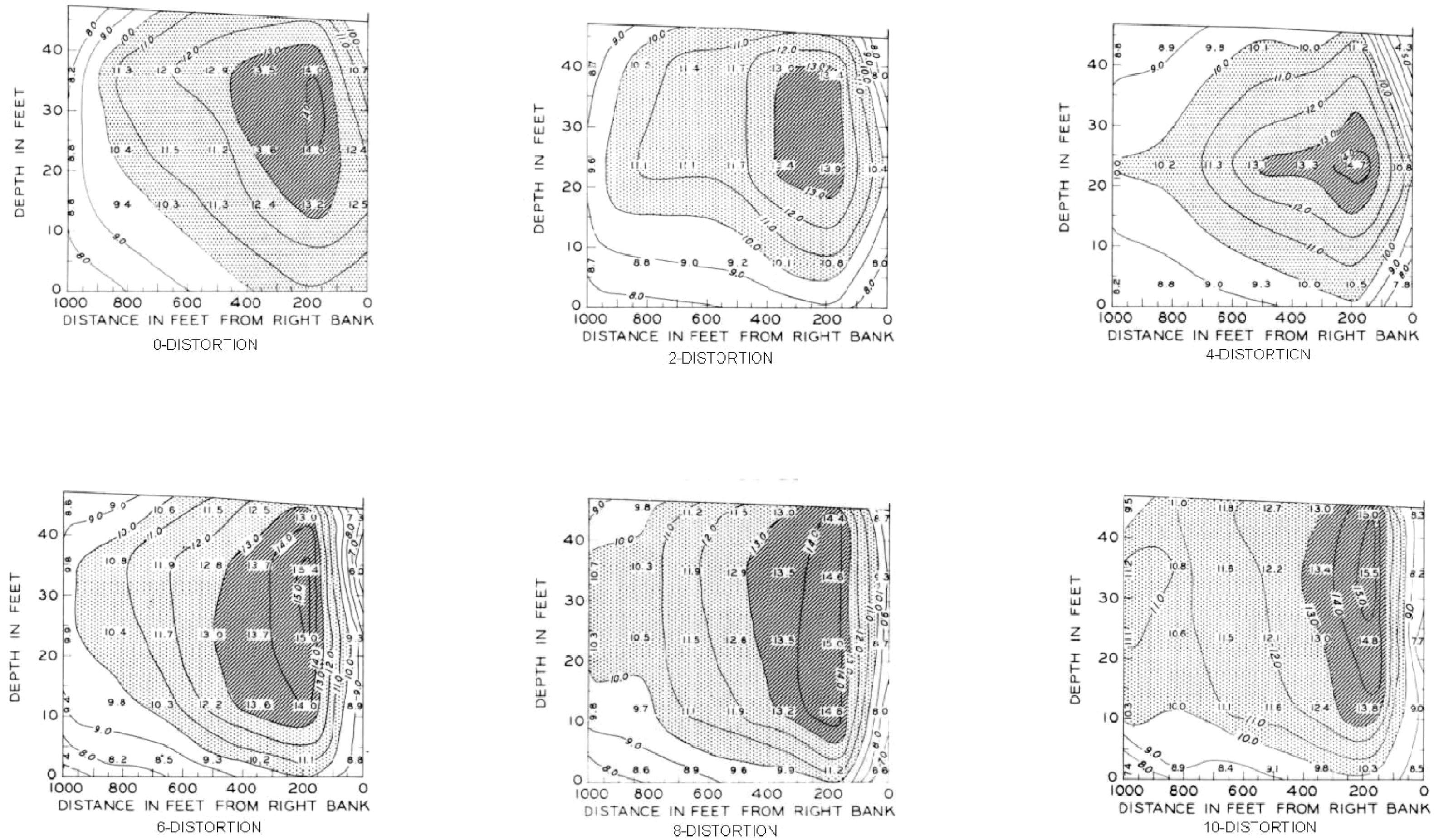
STATION 52+00



EFFECT OF MODEL DISTORTION

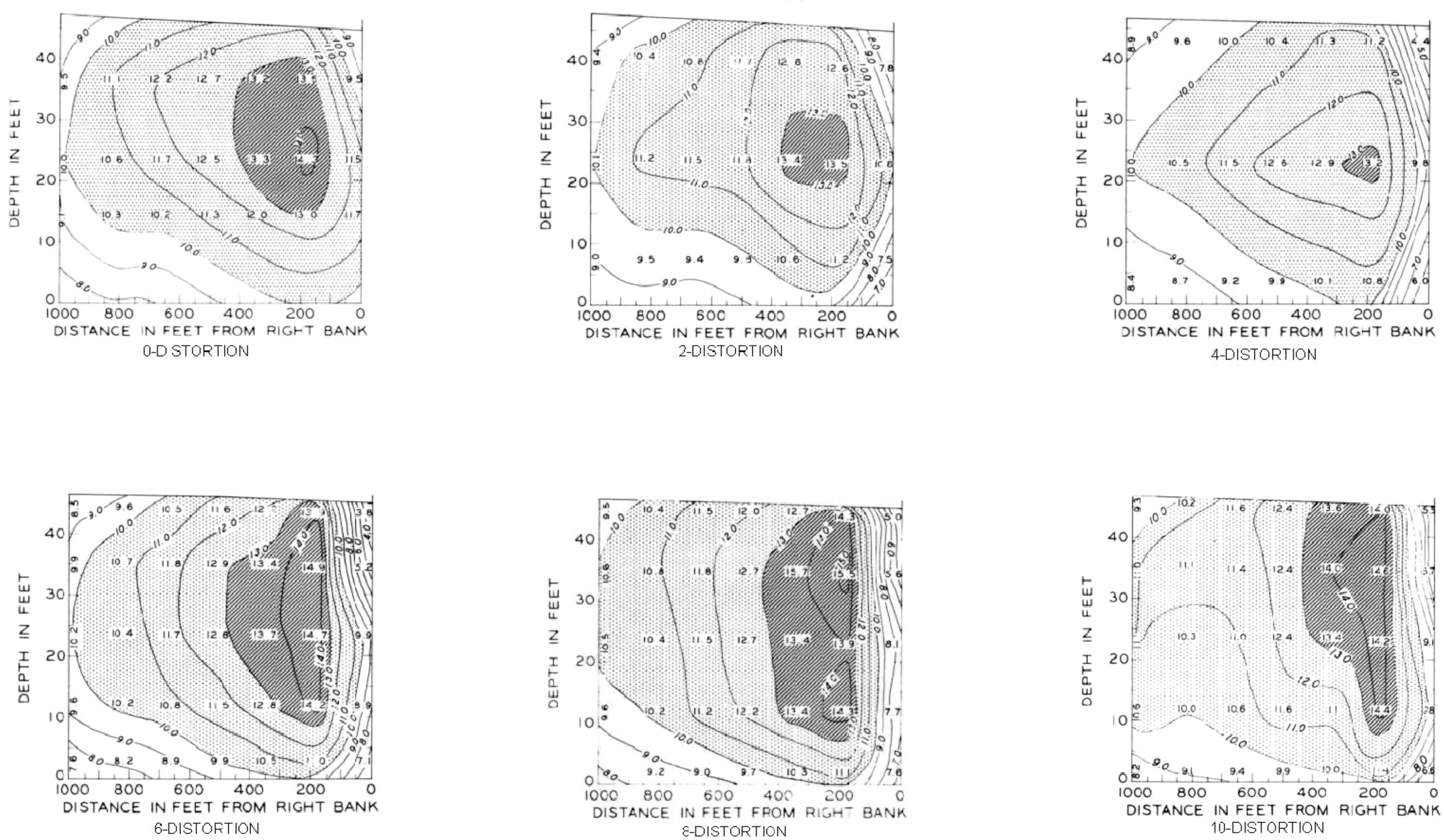
VELOCITY CROSS SECTIONS
PLAN A

STATION 56+00



EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS
PLAN A
STATION 60+00

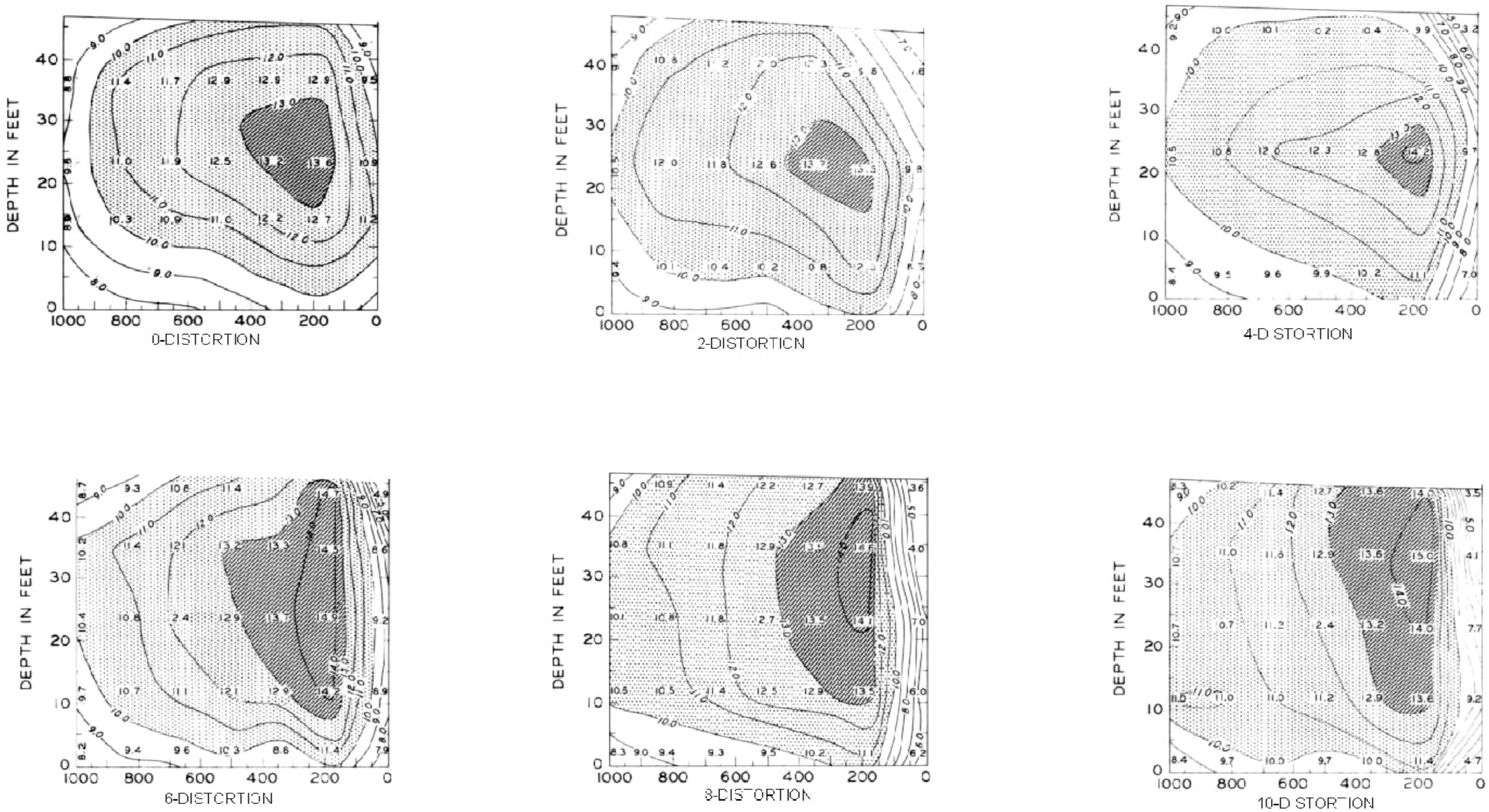


EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS

PLAN A

STATION 64+00

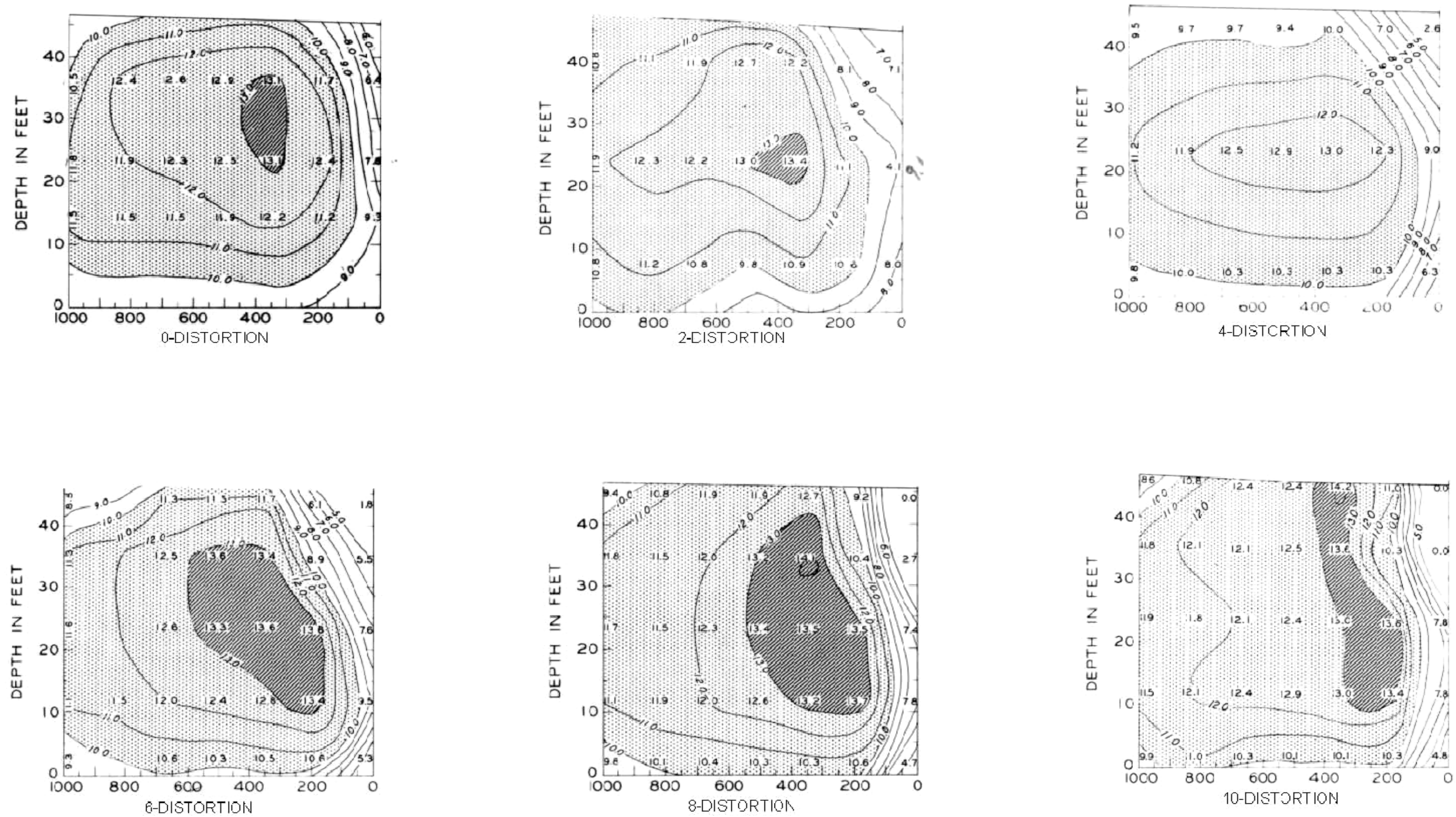


EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS

PLAN A

STATION 68+00

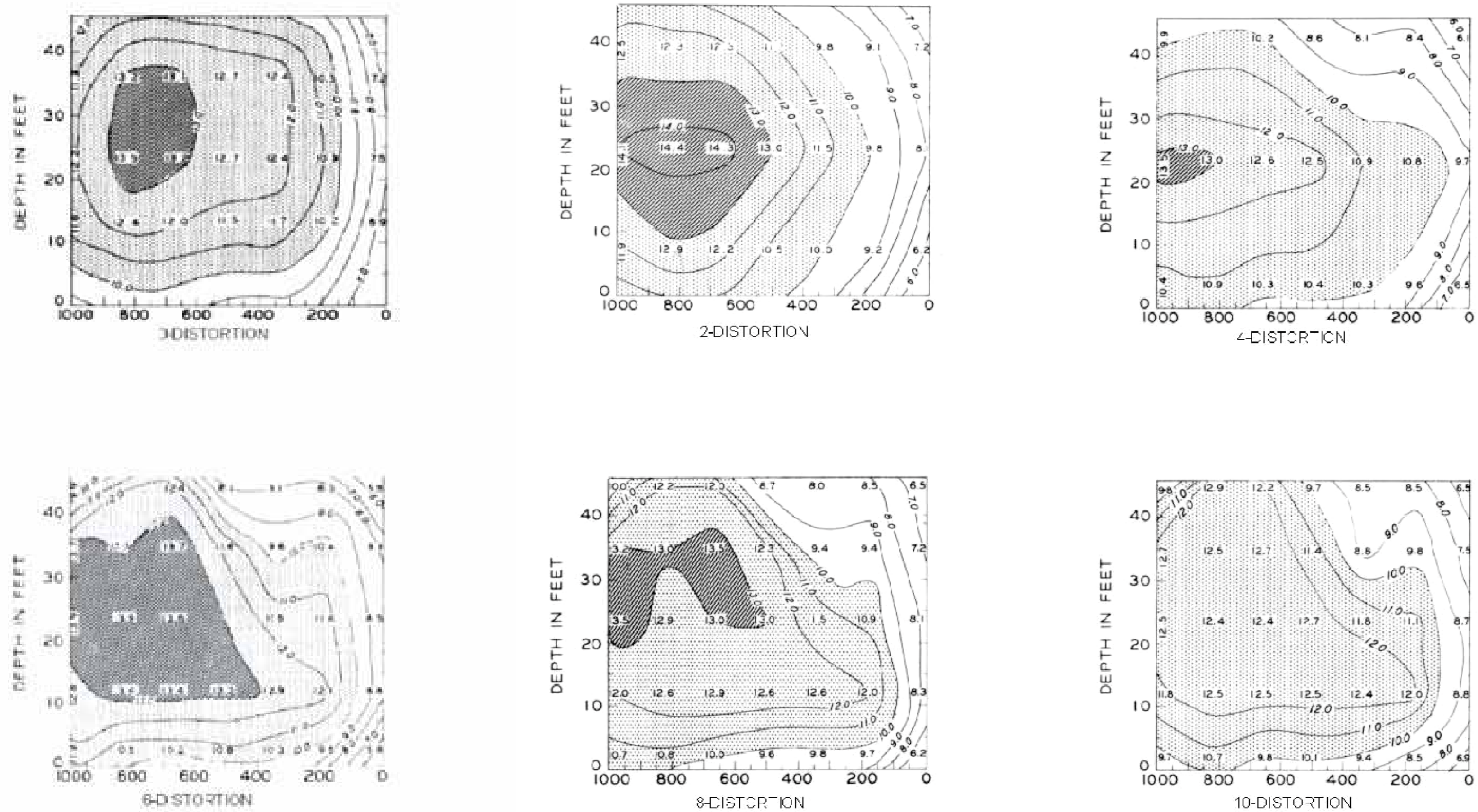


EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS

PLAN A

STATION 71+41.6

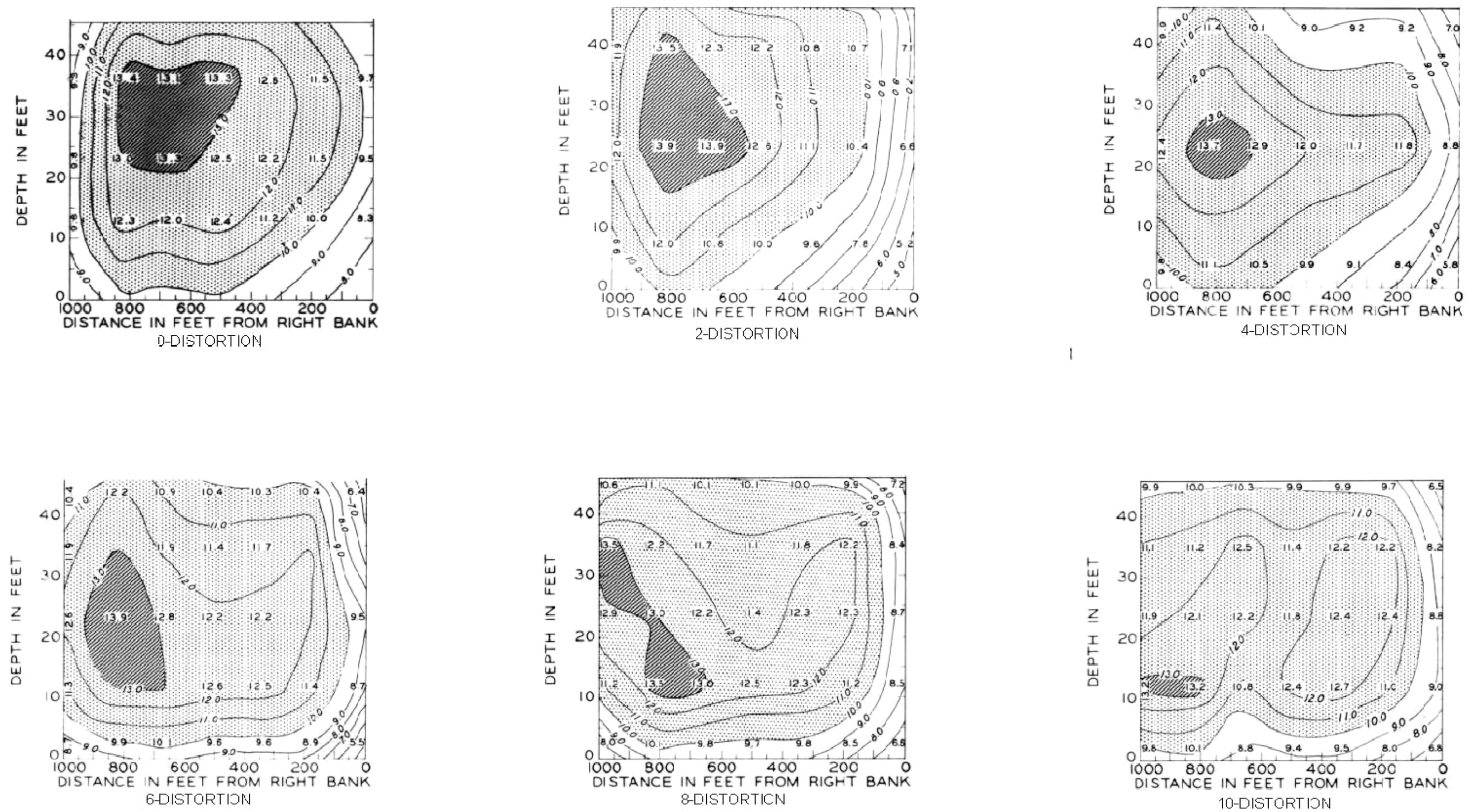


EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS

PLAN A

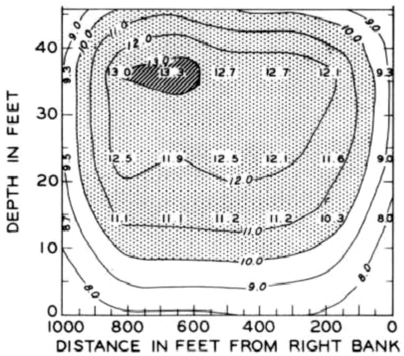
STATION 90+00



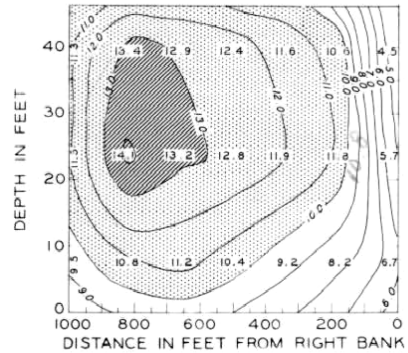
EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS
PLAN A

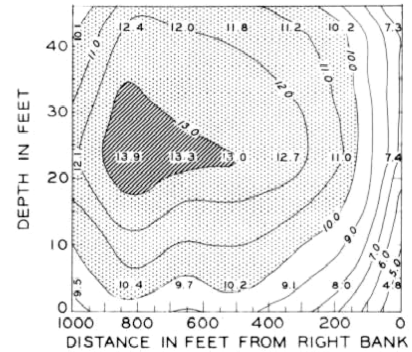
STATION 130+00



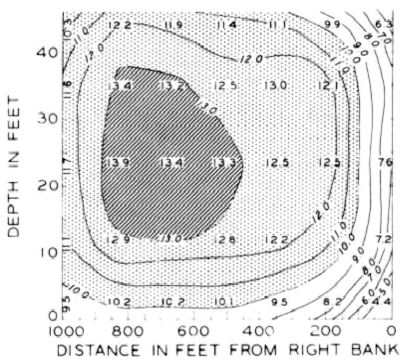
0-DISTORTION



2-DISTORTION



4-DISTORTION



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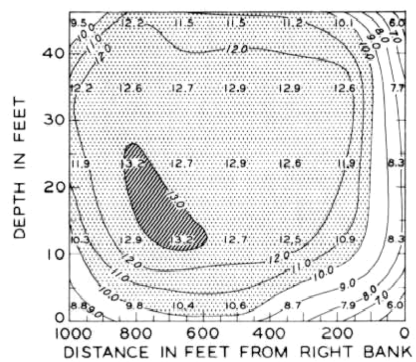
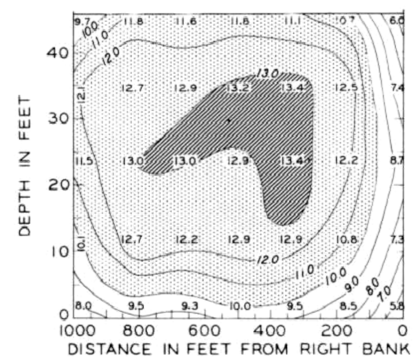


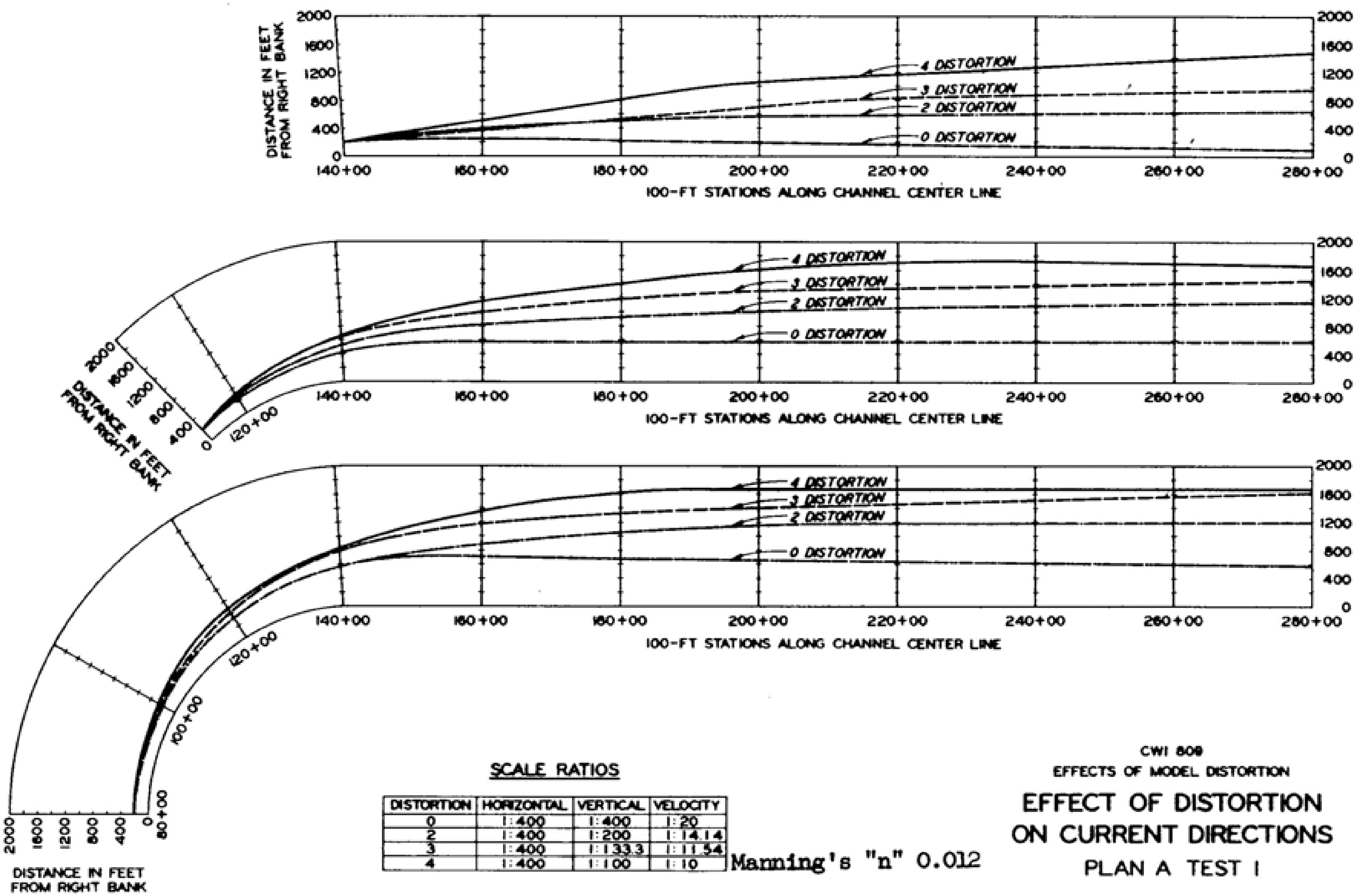
8-DISTORTION



10-DISTORTION

EFFECT OF MODEL DISTORTION

VELOCITY CROSS SECTIONS
PLAN A
STATION 190+00



SCALE RATIOS

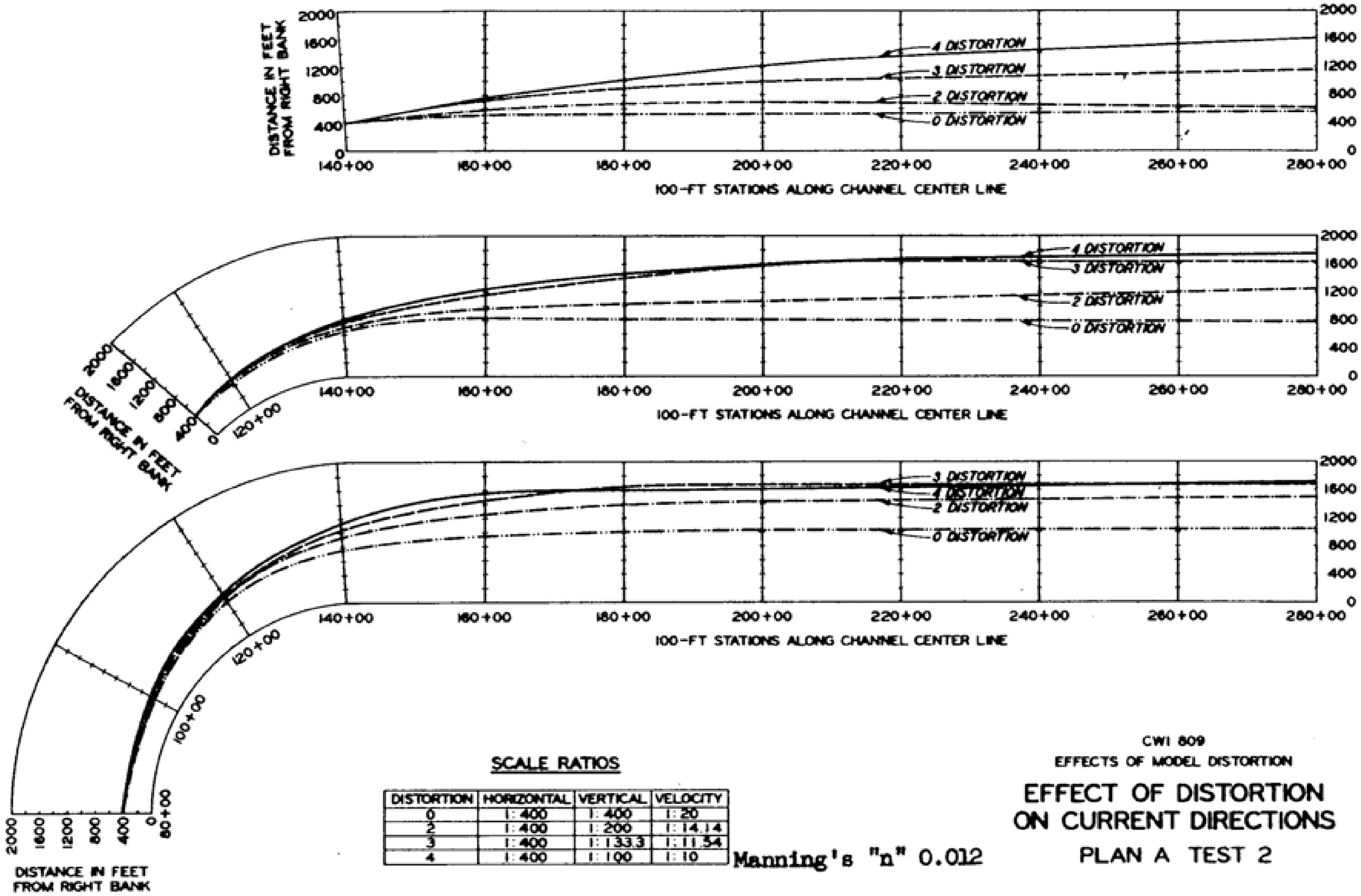
DISTORTION	HORIZONTAL	VERTICAL	VELOCITY
0	1:400	1:400	1:20
2	1:400	1:200	1:14.14
3	1:400	1:133.3	1:11.54
4	1:400	1:100	1:10

Manning's "n" 0.012

CWI 809
EFFECTS OF MODEL DISTORTION

EFFECT OF DISTORTION ON CURRENT DIRECTIONS

PLAN A TEST I



SCALE RATIOS

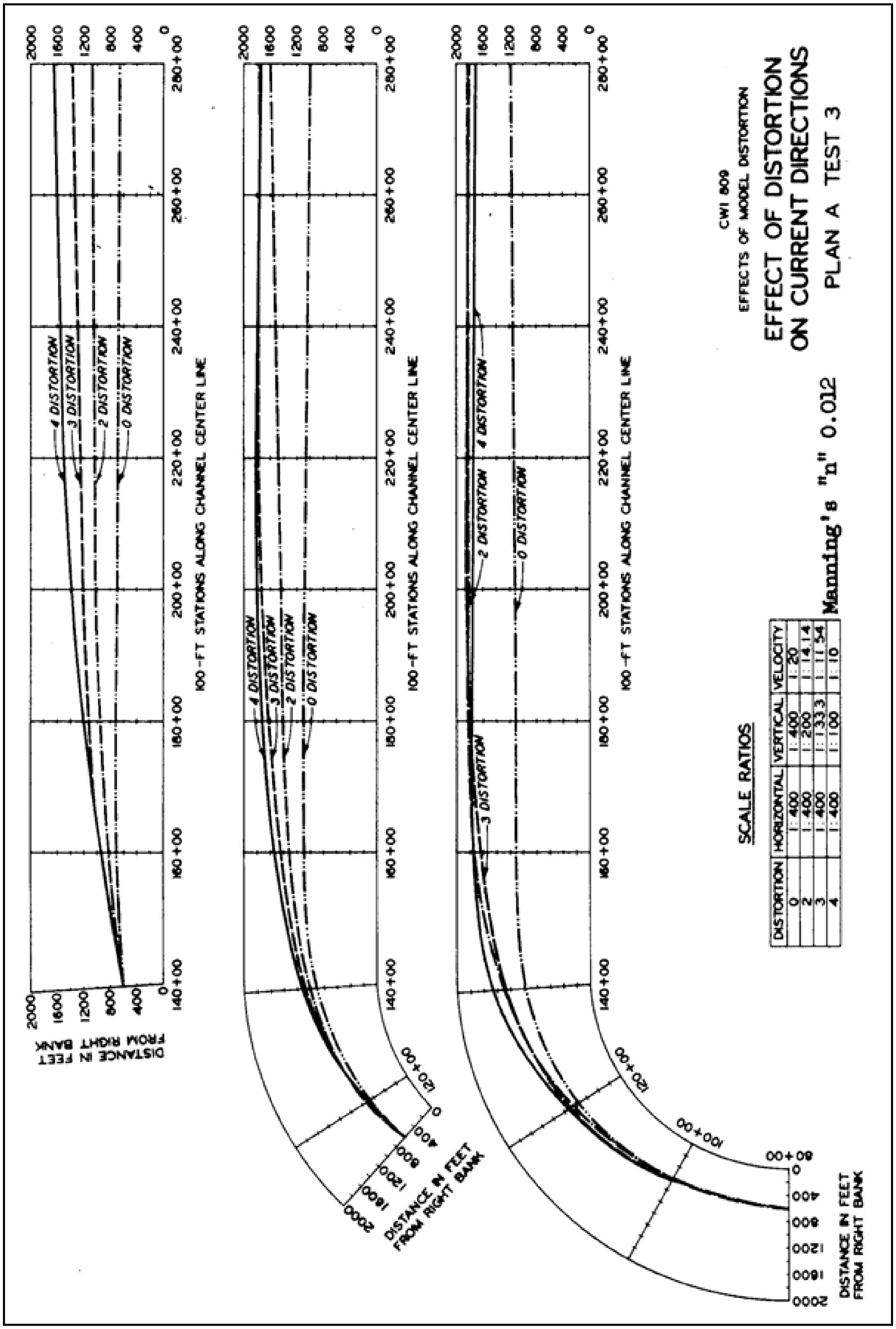
DISTORTION	HORIZONTAL	VERTICAL	VELOCITY
0	1:400	1:400	1:20
2	1:400	1:200	1:14.14
3	1:400	1:133.3	1:11.54
4	1:400	1:100	1:10

Manning's "n" 0.012

CWI 809
EFFECTS OF MODEL DISTORTION

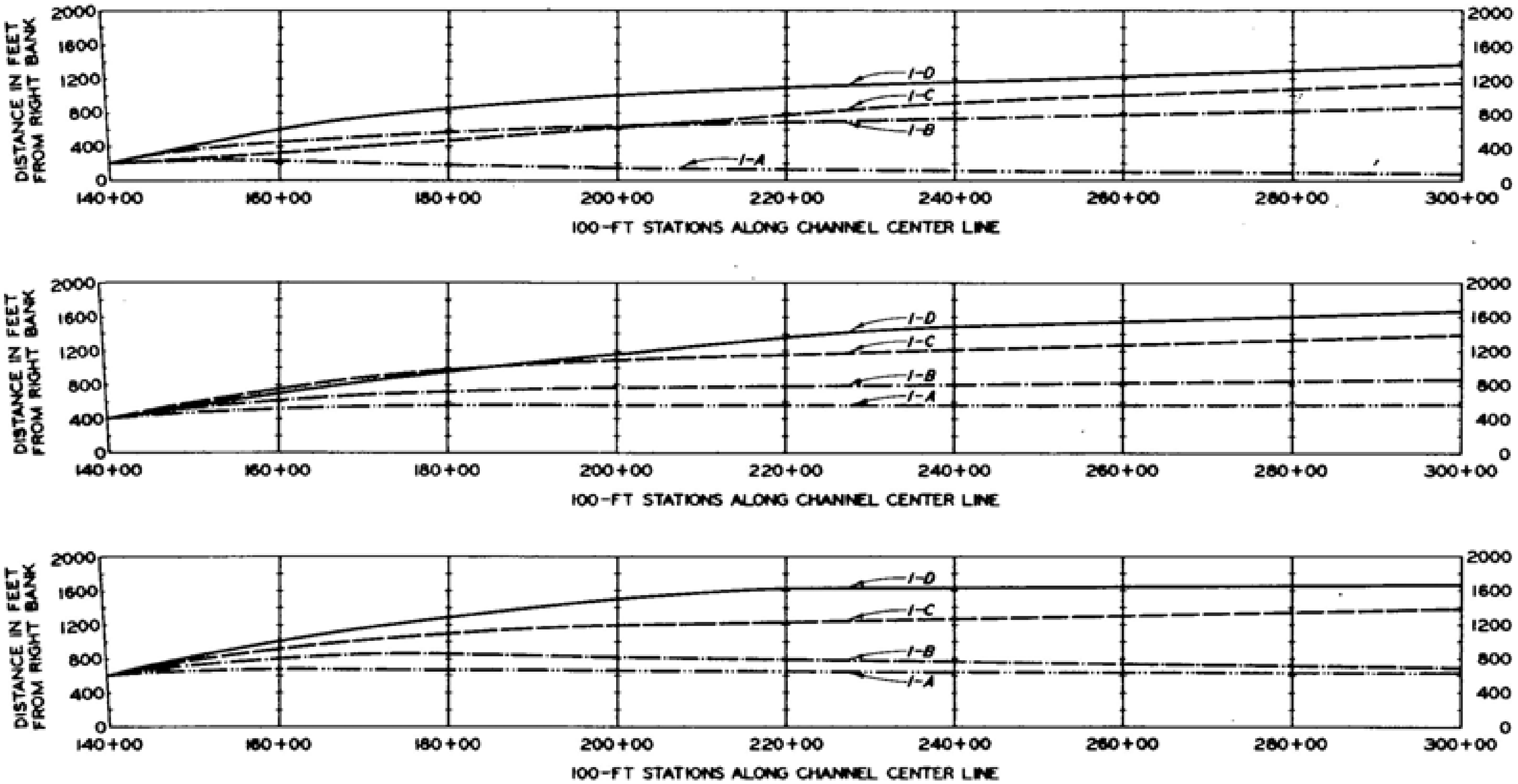
EFFECT OF DISTORTION ON CURRENT DIRECTIONS

PLAN A TEST 2



CWI 809
EFFECTS OF MODEL DISTORTION
EFFECT OF DISTORTION
ON CURRENT DIRECTIONS
PLAN A TEST 3
Manning's "n" 0.012
SCALE RATIOS
DISTORTION | HORIZONTAL | VERTICAL | VELOCITY
0 | 1:400 | 1:400 | 1:20
2 | 1:400 | 1:200 | 1:14.14
3 | 1:400 | 1:133 | 1:11.54
4 | 1:400 | 1:100 | 1:10
4 DISTORTION
3 DISTORTION
2 DISTORTION
0 DISTORTION
100-FT STATIONS ALONG CHANNEL CENTER LINE
DISTANCE IN FEET FROM RIGHT BANK

Plate 46



SCALE RATIOS

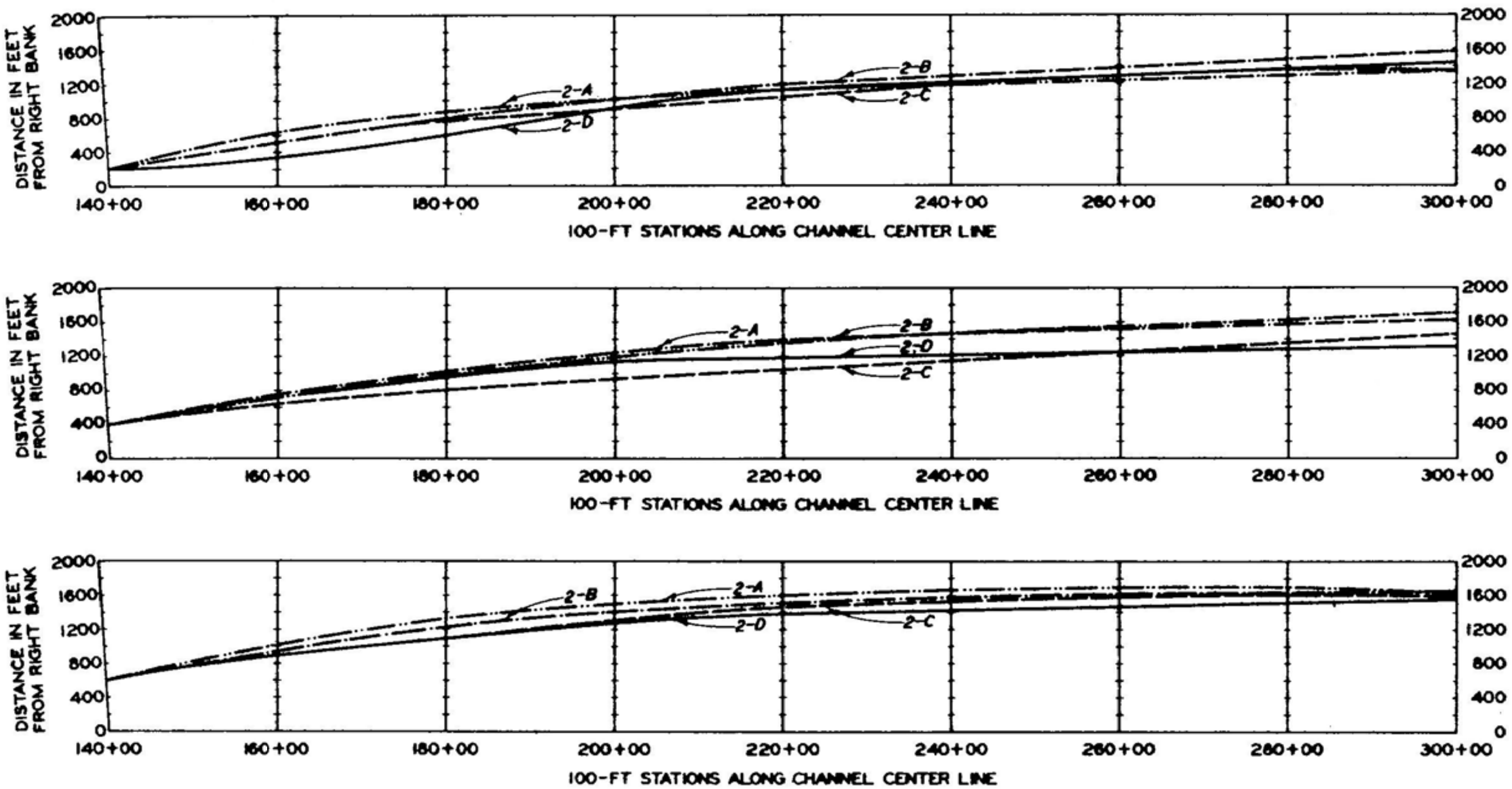
SCHEME	HORIZONTAL	VERTICAL	VELOCITY
I-A	1:400	1:400	1:20
I-B	1:400	1:200	1:20
I-C	1:400	1:133.3	1:20
I-D	1:400	1:100	1:20

Velocity constant
Manning's "n" 0.012

CWI 809
EFFECTS OF MODEL DISTORTION

EFFECT OF VARYING DEPTH ON CURRENT DIRECTIONS

PLAN A TEST 7



SCALE RATIOS

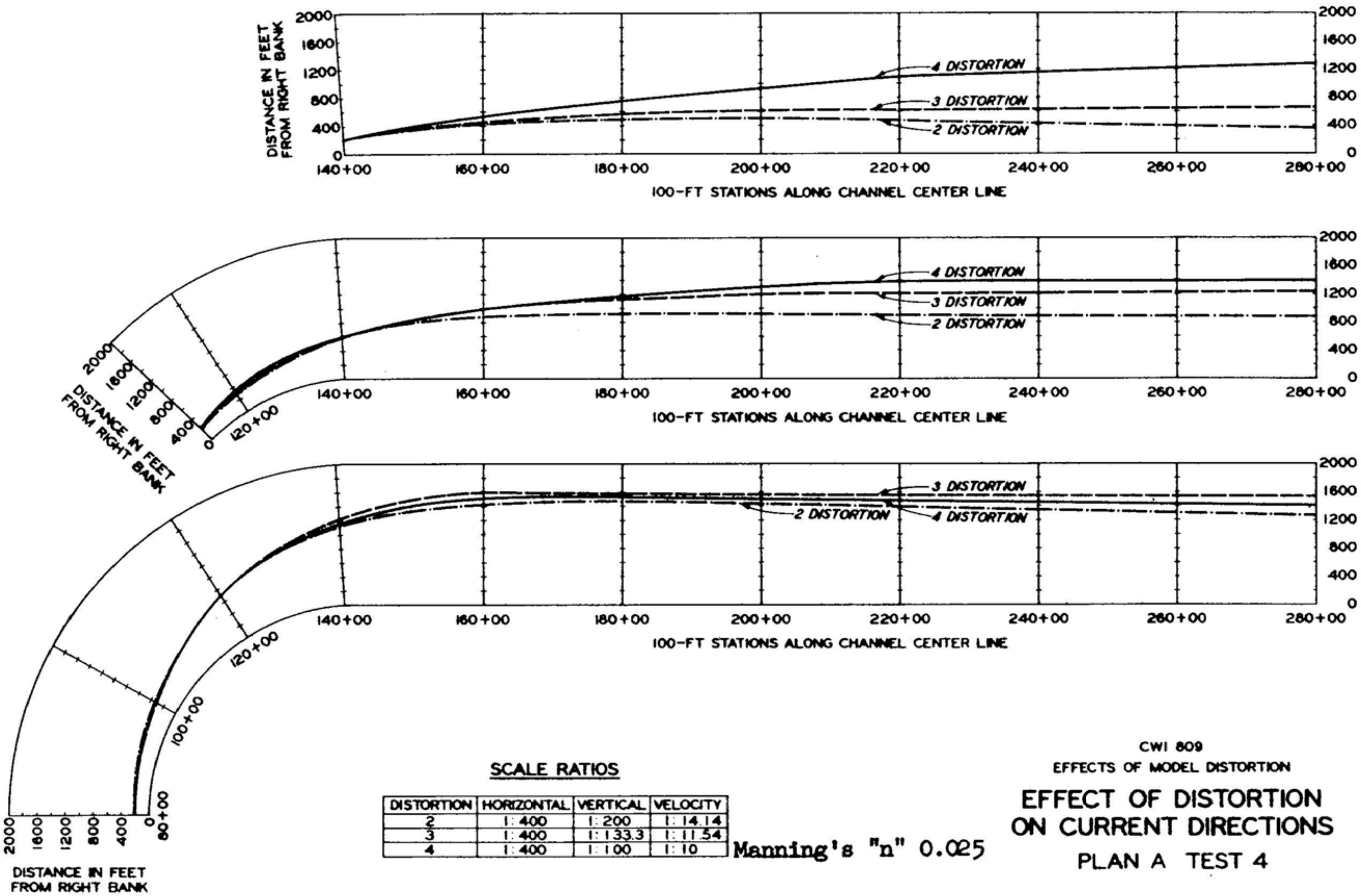
SCHEME	HORIZONTAL	VERTICAL	VELOCITY
2-A	1:400	1:100	1:20
2-B	1:400	1:100	1:10
2-C	1:400	1:100	1:70.7
2-D	1:400	1:100	1:50

Depth constant
Manning's "n" 0.012

CWI 809
EFFECTS OF MODEL DISTORTION

EFFECT OF VARYING VELOCITY ON CURRENT DIRECTIONS

PLAN A TEST 8



SCALE RATIOS

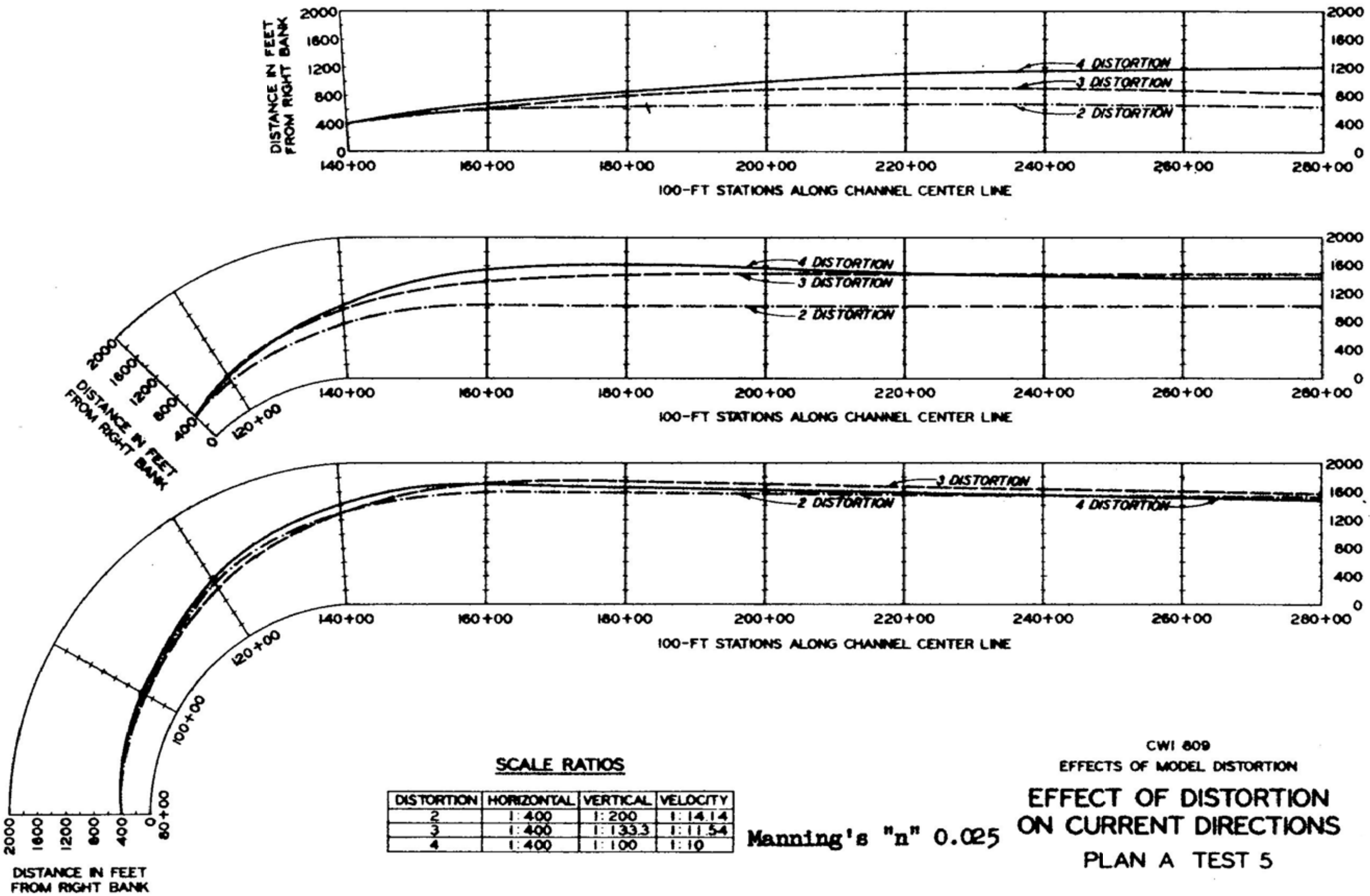
DISTORTION	HORIZONTAL	VERTICAL	VELOCITY
2	1:400	1:200	1:14.14
3	1:400	1:133.3	1:11.54
4	1:400	1:100	1:10

Manning's "n" 0.025

CWI 809
EFFECTS OF MODEL DISTORTION

EFFECT OF DISTORTION ON CURRENT DIRECTIONS

PLAN A TEST 4



SCALE RATIOS

DISTORTION	HORIZONTAL	VERTICAL	VELOCITY
2	1:400	1:200	1:14.14
3	1:400	1:133.3	1:11.54
4	1:400	1:100	1:10

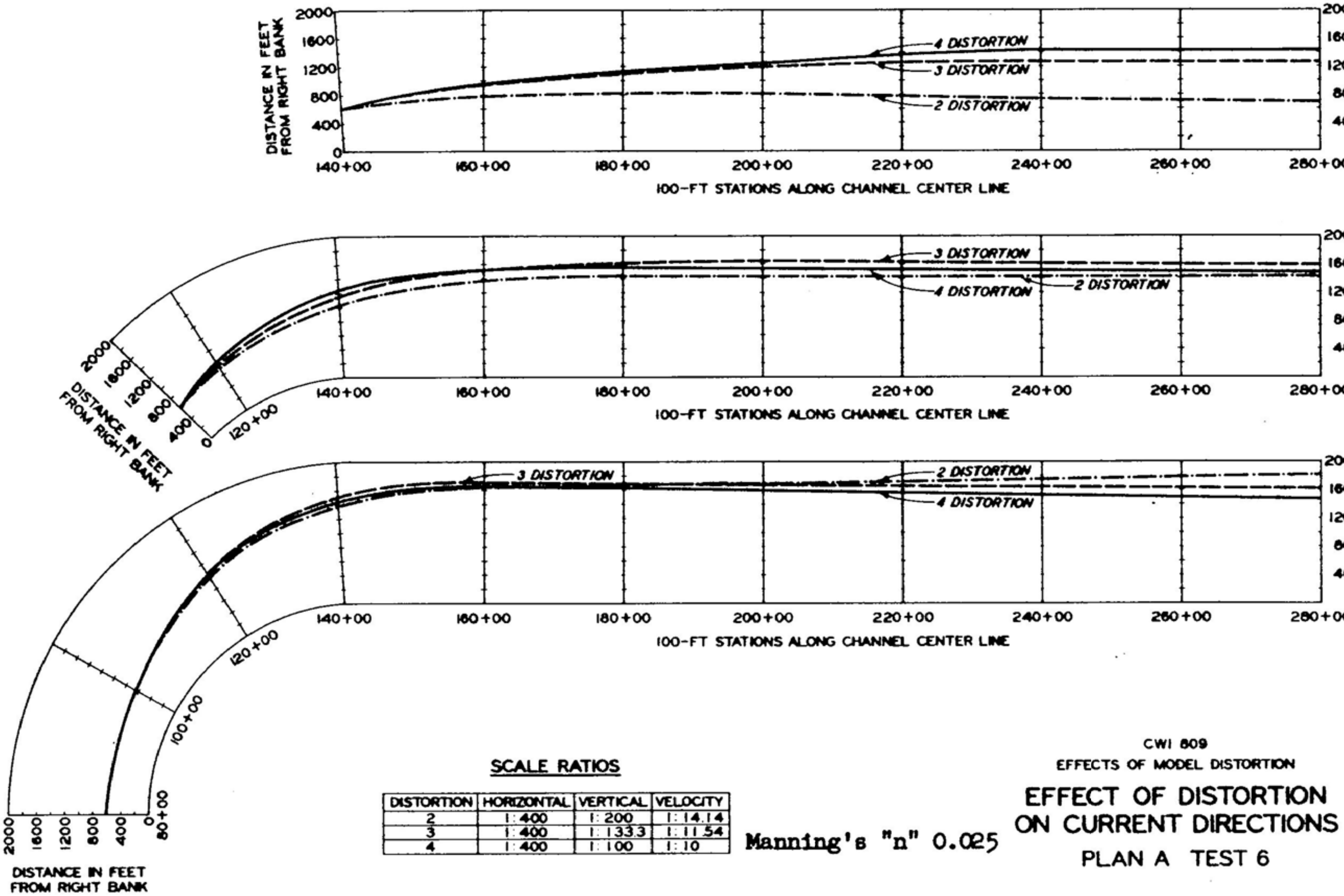
Manning's "n" 0.025

CWI 809

EFFECTS OF MODEL DISTORTION

EFFECT OF DISTORTION ON CURRENT DIRECTIONS

PLAN A TEST 5



SCALE RATIOS

DISTORTION	HORIZONTAL	VERTICAL	VELOCITY
2	1:400	1:200	1:14.14
3	1:400	1:133.3	1:11.54
4	1:400	1:100	1:10

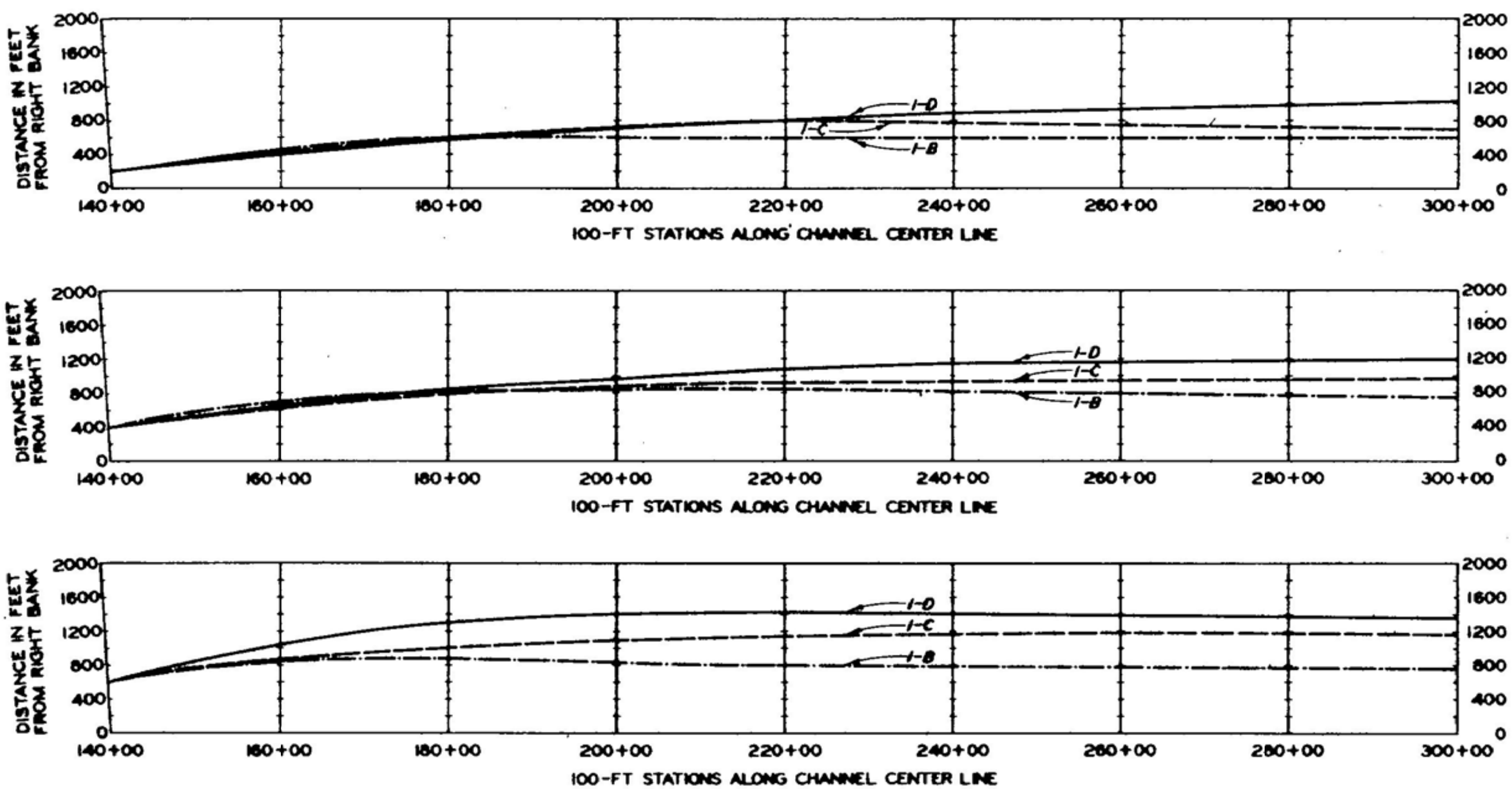
Manning's "n" 0.025

CWI 809

EFFECTS OF MODEL DISTORTION

EFFECT OF DISTORTION ON CURRENT DIRECTIONS

PLAN A TEST 6



SCALE RATIOS

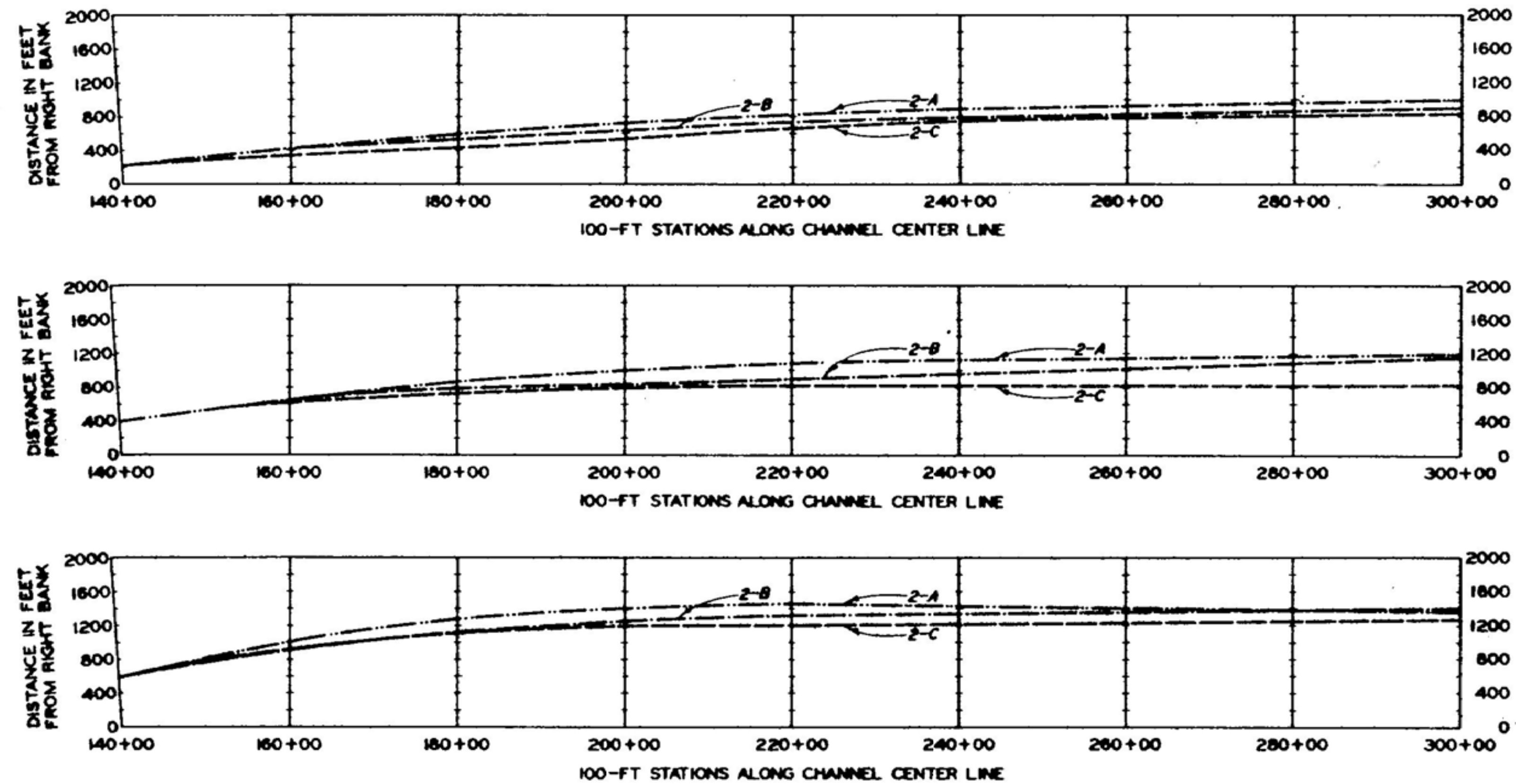
SCHEME	HORIZONTAL	VERTICAL	VELOCITY
I-B	1:400	1:200	1:20
I-C	1:400	1:133.3	1:20
I-D	1:400	1:100	1:20

Velocity constant
Manning's "n" 0.025

CWI 809
EFFECTS OF MODEL DISTORTION

EFFECT OF VARYING DEPTH ON CURRENT DIRECTIONS

PLAN A TEST 10



SCALE RATIOS

SCHEME	HORIZONTAL	VERTICAL	VELOCITY
2-A	1:400	1:100	1:20
2-B	1:400	1:100	1:10
2-C	1:400	1:100	1:707

Depth constant
Manning's "n" 0.025

CWI 809
EFFECTS OF MODEL DISTORTION

EFFECT OF VARYING VELOCITY ON CURRENT DIRECTIONS

PLAN A TEST 9

REPORT DOCUMENTATION PAGE

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5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Thomas J. Pokrefke, Jr.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

In the 1930s, 1940s, and 1950s, the U.S. Army Engineer Waterways Experiment Station (WES) conducted several series of studies to investigate the effects of distortion, differing horizontal and vertical scales, on physical model results. This report presents the portion of those investigation conducted from 1954 to 1961. The results had not been previously published; however, the two WES researchers, the late Messrs. John J. Franco and the late James E. (Ed) Glover, had prepared various unpublished documents of these investigations. Therefore, this report is a compilation of those writings and supporting data, as well as this author's conclusions and applicability of the effects of distortion investigations to physical, movable-bed models using lightweight bed materials.

The investigations conducted by Franco and Glover involved two specific series of tests. Those series were:

a. Plan A, Series 1. These tests were conducted using distortions of 0, 2, 4, 6, 8, and 10. The horizontal scale used was 1:200 with subsequent vertical scales of 1:200, 1:100, 1:50, 1:33.33, 1:25, and 1:20, respectively. The tests were conducted following the Froude criteria to determine the appropriate velocity and discharge scales for these tests.

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15. SUBJECT TERMS

Distorted depth	Fixed-bed model	Model distortion
Distorted velocity	Froude relationships	Movable-bed model
	Lightweight bet material	

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b. Plan A, Series 2. These tests were conducted using distortion ratios of 0, 2, 3, and 4. The horizontal scale used was 1:400. This series of tests was conducted somewhat different than Series 1, with the velocity held constant at the 0-distortion value and the depth varied from the 0-distortion to the 4-distortion value. The depth was then held at the 4-distortion value and the velocity varied from the 0-distortion to the 4-distortion value. Some of these tests were conducted with the Froudian scale relationships not followed to isolate either velocity or depth of flow impacts.

The results of the two series of tests conducted by Franco and Glover indicate that:

a. Based on the Series 1 tests, the effects of distortion on the results of models of a straight reach are negligible unless the flow is affected by a bend upstream.

b. Based on the Series 1 tests, flow around bends is affected by model distortion, and the effect extends for a considerable distance downstream depending upon the amount of distortion.

c. Based on the Series 1 tests, the current directions in models with distortions of 4 and higher and with curvilinear flow is affected to the degree that the influence extends to the downstream model limits.

d. Based on the Series 2 tests, the currents in a bend would be deflected toward the concave side of the channel as the linear-scale distortion is increased. The effect of distortion was generally progressive up to a point where the alignment of the currents was affected or controlled by the wall along the concave side of the bend. When this point was reached, increasing the distortion appeared to have little effect on the alignment of the currents.

e. Based on the Series 2 tests, with the same channel roughness, the factors varied as the model was distorted were velocity and depth. The test results with constant depth and with constant velocity indicated that changes in the width-depth ratio of the channel was the principal cause of the deviation in the alignment of currents in a bend.

f. Based on the Series 2 tests, increasing the roughness of the model channel as the distortion was increased would tend to reduce the effect of distortion. These results also tended to indicate that use of surface roughness sufficient to entirely overcome the effect of distortion would be impracticable.